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ANALYTICAL EVALUATION OF UNREP METHODS
USING THE MODEL bFORM

by

Steven L. Barnaby

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Thesis Advisor: W. P. Hughes

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Using the results from a model called BFORM, the thesis gives an analytical evaluation of the trade offs between two methods of UNREP (delivery boy and service station). Results show quantitatively the extent of the advantage of the delivery boy method over the service station method. The advantage held for all circumstances investigated.

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Analytical Evaluation of UNREP Methods Using the Model BFORM

by

Steven L. Barnaby
Lieutenant, United States Navy
B.S., Pennsylvania State University, 1982

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Author: ______________________
Steven L. Barnaby

Approved By: ______________________
Wayne P. Hughes, Thesis Advisor

____
Dan C. Boger, Second Reader

____
Peter Purdue, Chairman,
Department of Operations Research

____
Kneale T. Marshall,
Dean of Information and Policy Sciences

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I. INTRODUCTION

This thesis concerns Battle Force/Group endurance and sustainability of U.S. warships at sea. In order to maximize the utility of the combatants within the Battle Group, they must remain on station ready to perform any assigned task. When a combatant is involved with Underway Replenishment (UNREP) operations, it is not performing the mission it was constructed to perform. To arrive, and remain, on UNREPstation at sea prepared to conduct prompt and sustained combat operations requires logistic services [Ref. 1].

This essential support must be integrated into each battle group. How the Battle Group Commander provides this service is a critical element to the on station time of the combatants. A readiness goal of the Battle Group Commander is to maximize the on station time. Is it better to let the combatants reach a lower level of fuel thereby remaining on station longer on the average, or is it better to keep them topped off at all times "to be ready"? If the answer is somewhere in between, then what is the trade off between the two?

This paper examines the trade offs between Speed Of Advance (SOA), UNREP speed, and the method of UNREP. Understanding these relationships may provide a Battle Force/Group Commander with additional insight on which to base his

his decisions not only on the tactical situation but also considering the logistic constraints.

By maintaining ship logistic readiness on station, the offensive and defensive postures of the Battle Group are kept intact [Ref. 1:p. ii]. This concern is at least on the same level of significance as ASW, AAW or ASUW readiness since none of these could be accomplished for very long without logistics.

In order for the Navy to carry out its mission, fleet units must be capable of remaining at sea for prolonged periods of time. Incorporating logistic implications of high SOA's or methods of UNREP in order to arrive at the launch point for power projection at the right time must be evaluated at the CWC level and integrated into the battle plan. Forward combatant logistics support is essential to maintain the combat effectiveness of the Battle Group.

A. BACKGROUND

In order to maximize the utility of units assigned to a battle group, the Navy has developed a system to resupply a battle force/group while at sea. This system is known as Replenishment At Sea (RAS). Ships of the Combat Logistics Force (CLF) are a critical part of this logistics system [Ref. 2]. They resupply combatants at sea with fuel, stores, and ammunition. Shuttle ships will transport the supplies to the battle groups. Once in the operating area, these shuttle ships will transfer their loads to the station ship, which is typically a fast combat support ship, that steams in the battle group formation. Using multi-product station ships to transfer supplies to the combatants within the battle group, an appropriate operational posture can be maintained and sustained. The appropriate posture is one which adequately maintains and sustains both offensive and defensive capabilities of the Battle Group [Ref. 3]. Replenishing combat ships from one stop station ships minimizes the time that the combat ships are involved in underway replenishment operations [Ref. 2:p. x]. The method by which this service is provided varies between: Delivery Boy; Service Station; and Moving Service Station. The Moving Service Station method is basically an UNREP somewhere in between a Delivery Boy and Service Station.

In this study only the delivery of Diesel Fuel Marine (DFM) and JP-5 is analyzed. The implicit assumption is that these are the constraining consumables, and that ammunition, food, and all other logistic requirements can be transferred concurrently. With regard to ammo, this will not always be the case, but this is true frequently enough to cover the vast majority of scenarios.

The most vulnerable time for a combatant is when it is alongside the logistics ship conducting Replenishment At Sea (RAS). Bringing the combatant in from the outer edge of the screen to a point in or near the center of the formation to be under the protective umbrella of the battle group may be impractical when considering the time the combatant will spend off station. However, sending the station ship out to the far edges of the screen, where it is highly vulnerable, can also be as impractical when considering the value of this asset.

Battle Groups have a mission-essential need for a high degree of logistical independence when deployed to forward areas. Current tactics and naval warfare doctrine normally require Carrier Battle Groups (CVBG) and other Task Groups to operate in dispersed formations to achieve defense in depth. Such formations also provide a degree of operational deception against potential enemy sensors. They present a unique set of factors which the Battle Group/Task Group Commander must consider when planning for underway replenishment operations in a multithreat environment. [Ref. 3:p. 1] His objective is to maintain the desired formation and combat readiness of all units in it. To do so he must minimize the time taken by logistics operations.

The individual tasked with battle group logistics is the Battle Force/Group Logistics Coordinator (BFLC/BGLC). The BFLC/BGLC frees the staff of the Composite Warfare Commander (CWC) from extensive logistics coordination to focus more upon warfighting coordination. The tactical organization provides for a Battle Force Logistics System (BFLS) which ensures that logistic support is consistent with the war fighting requirements of the Battle Force/Group. The goal of this system is to anticipate and identify requirements, identify and allocate resources, develop methods of monitoring support and measure the response of the BFLS through specified required reports. The BFLC provides recommendations and implements decisions on logistics by the Commander Task Force/Group (CTF/CTG) and the CWC. He will modify logistics operations to fit the needs of the battle force and ensure that all needs in the functional areas are being met. The expressed philosophy of BFLS operations is one of early or pre-emptive response to emerging problems and commitments. This will enable the execution of a plan of action to provide support without further guidance or tasking from the CWC. [Ref. 4]

Replenishment plans must be in consonance with the CWC's operational intentions and vice versa. A look at the trade offs between the types of UNREP and the effects of factors such as SOA and UNREP speed will enable the BFLC and CWC to evaluate the decision of what type of UNREP and where it will take place, along with what level of fuel state is considered appropriate to initiate the UNREP. The BFLC must ensure that logistics coordination makes tactical sense and monitor tactical evolutions to advise the CWC if situations are undesirable logistically.

II. THE MODEL BFORM

Battle Force Operation Replenishment Model, BFORM, is a microcomputer based simulation of intra-battle force resupply. BFORM was written as a planning aid as part of a larger study of the use of station ships. BFORM was written by programers at the Applied Physics Laboratory Johns Hopkins University for Chief of Naval Operations, Program Resource Appraisal Division OP-81. The model runs on IBM or compatible PC's and allows the user to examine the consequences of different choices of station ship design and operational methodology [Ref. 5].

BFORM provides a number of different results which may be expressed to measure the effectiveness of the battle force replenishment process. Two primary results relate to operational off station time and commodity inventory levels. Operational off station time is defined as the total time each ship is off its assigned station. Included in this output is the total time the station ship is alongside a combatant involved in UNREP. Output data is provided on inventory levels of 15 commodities for each ship in the battle force. Commodity data includes the minimum levels reached, the average levels maintained, and the standard deviation of each commodity.

With respect to time, output data is also provided on the maximum time each combatant spent away from its assigned station. Basically, this is just the largest single time off station for each combatant during the simulation run. Again, operational off station time is the total (cumulative) time each ship spends off station. Operational off station time includes not only UNREP time but also the transit time needed for the combatant to either regain its station after replenishment or to leave its station and rendezvous with the station ship, UNREP, and return to station. UNREP time includes the time to transfer the needed commodities to fill the combatant plus 20 minutes. This additional 20 minutes is for approach, connecting and disconnecting, and is a reasonable amount of time to add to cover these events. Because of the large number of potential variables and scenarios, and as a result of making BFORM as flexible as possible, it is a complex model.

In BFORM, ships are given a mission type: combatants, station ships, shuttle ships, and escorts for station and shuttle ships. The model allows any class of ship to be assigned to these missions. A combatant is characterized by staying within an operating radius (patrol area) that is fixed in the formation grid. The only time a combatant ship leaves this area is when it is involved in an UNREP operation. DFM is expended based on ship class fuel expenditure characteristics and the current fuel use per unit speed.

JP-5 is expended based on the aircraft sortie rate for that ship (usually aircraft carriers) and a user supplied fuel expenditure rate per sortie. This sortie rate can be modified by a user supplied event which may be used to simulate surges or stand downs. Station ships remain with the battle force through out the simulation run and supply commodities (POL and ordnance) to the combatants and escorts. Shuttle ships appear at a user defined time and then act as station ships with the capability of supplying combatants or can be specified to console directly with a station ship. When shuttle ships run below a preset level of supplies they leave the formation. Escorts are similar to combatants except that they go everywhere their assigned station or shuttle ship goes, instead of staying on a fixed station. [Ref. 5:p. 2-2]

Three methods of resupply are possible. The first is called "Delivery Boy", which performs the resupply at the receiving ships station in the formation within the ships patrol area. The station ship goes to each ship in turn based on some scheduling algorithm. If the station ship is outside of the receiving ship's patrol radius, the initial rendezvous for an UNREP takes place at the point on the circumference of the patrol area nearest to the station ship. The station ship moves at designated ("flank") speed between ships. Once an UNREP begins, the ship is moved at the UNREP speed in the direction determined by the sea direction. Sea direction is a user supplied event. In the event that the receiving ship leaves its patrol area during the UNREP, it will return to its patrol area at flank speed and the time it takes to regain station will be added to its cumulative off station time. The station ship will then proceed to its next UNREP (if one can be scheduled). If no UNREP is scheduled then the station ship will proceed on formation base course and speed at its current position at the end of the last UNREP.

The second method, "Service Station", is similar to an auto gas station. The point of initial rendezvous for an UNREP is always the assigned position of the station ship. The replenishment ship stays on a fixed station in the formation, and each combatant comes to the station ship. The UNREP station stays fixed throughout the simulation run. In the event that the station ship and the combatant should fall behind during UNREP (when UNREP speed is less than SOA), the station ship will always return to its station before starting another UNREP. In this mode, the station ship can service two ships at once.

The third method, "Moving Service Station", allows the operator to define locations, called phantom ship positions, at which resupply takes place. Under this method there can be several locations through out the formation at which resupply takes place. From these phantom ship locations resupply proceeds identical to the Service Station method.

The variable determining when a unit is off station and controlling when a unit is allowed to UNREP with the station ship is called the patrol radius. In order for a ship to be considered for UNREP it must be within the distance of the patrol radius. The patrol radius for the station ship will determine which ships will be allowed to UNREP under the Service Station and Moving Service Station methods. The patrol radius for the combatant is utilized when using the Delivery Boy method as described above.

Scheduling of an UNREP is based on user supplied priorities as well as current commodity levels and availabilities aboard the station or shuttle ship. All UNREPs are scheduled from one algorithm depending on which method of UNREP was chosen. UNREPs are scheduled on the basis of the demand at the time the station or shuttle ship becomes available as well as the distance from the station or shuttle ship to the receiving ship. The user supplied priorities provide the policy guidelines used in the decision making process of the scheduling algorithm, which acts in the following way. [Ref. 5:p. 2-2]

The station ship searches through all of the other ships in the formation not already involved in UNREP in order to determine the level of each commodity. The commodity level is expressed as the ratio of the current level to that of the absolute capacity. If a commodity level is greater than the upper threshold (a user supplied input which is commonly called a flag to initiate a need for UNREP), then it is assigned a value greater than one so that it is not considered for possible UNREP. A level below the upper threshold will place the ship in the queue for UNREP. Another user supplied threshold level is the lower threshold level. When a unit falls below the lower threshold level it is considered to have a critical need for UNREP and is placed ahead of other units which were flagged when they fell below the upper threshold level. Each of the ships placed into the queue is then assigned a priority number based on the weighted average of its commodity levels multiplied by the minimum weighted commodity level. The weights used are the product of the normalized ship class priority and the normalized commodity priority. The priority number is then multiplied by the ship's distance from the station ship normalized by the distance of the furthest ship considered for UNREP. The scheduling station ship will perform the UNREP unless there is another free station ship closer to the selected ship. [Ref. 5:p. 2-4] Figure 1 illustrates the scheduling algorithm. [Ref. 5:p. 2-5]

Data entered in the model by the user include: battle force composition, each ship's formation position and speed, ship characteristics, i.e., fuel consumption rate for various speeds, fuel capacities, ordnance capacities, transfer rates and starting levels for each commodity; ship and commodity priority levels; combatant flight operations,

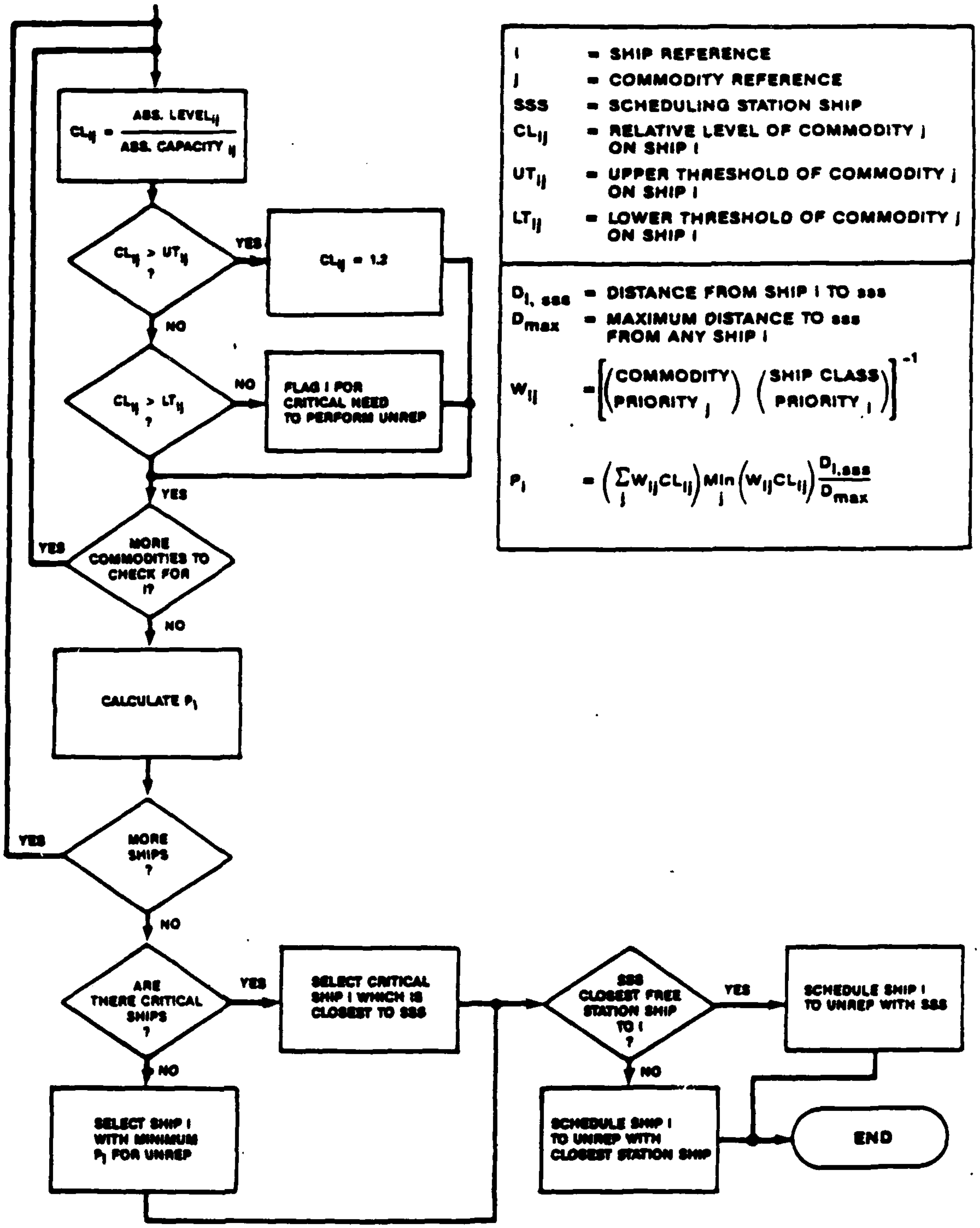

Figure 1. Flow Chart of Scheduling Algorithm

i.e., sorties per day; fuel usage per sortie; UNREP speed; and scheduled events such as ordnance expenditures, shuttle ship arrivals or changes in weather conditions. Information on weather conditions can be entered into what is called the events file. Weather events can degrade transfer rates and cause UNREPs to take place in a direction other than base course. This is due to the idea of UNREPing either away from the direction of the sea or into it and could cause the UNREP course to be up to a maximum of 90 degrees off base course. This will cause an additional delay in regaining station after UNREP.

The program models the battle group formation, based on a cartesian grid, moving on a base course of 000 degrees relative and at the entered SOA. The duration of a single simulation run is determined by the user, and is entered prior to the start, as a number of days. Resupply will be provided using one of the three methods described above. Fuel consumption is continuous and automatic, depending upon the consumption rates entered and based upon the ship's current required speed. Each combatant operates within a certain patrol radius around its assigned position. The operator can not change this radius once the simulation run has started. The effect of increasing the patrol radius is to reduce the time "off station" due to refueling.

Output from the model includes: commodity history file, which lists all changes to each commodity according to time;

event history file, lists all events that cause a change in the formation e.g., ship leaves to UNREP etc; summary statistics on all 15 commodity levels; and statistics on off station time for all ships in the formation. Commodity history file gives chronological information about each ship's commodity levels and records any major change, such as if a unit UNREPs or there is an expenditure of ordnance. A snapshot is taken and recorded in the commodity history file. The event history file provides a chronological history of all significant events during the simulation run. Summary statistics on commodity levels display the time weighted mean level for all 15 commodities on each ship. Also given are the standard deviations associated with the means. Another statistical output is the minimum level of each commodity reached by each combatant during the simulation run.

The operational off station time output gives two quantities, one for the longest single time each combatant was off station, i.e., outside its patrol radius, and the second is the sum of all the time spent off station. Remember that on station means within a ship's patrol radius and not involved with UNREP. Using these output files, MOEs can be developed, measured, and evaluated. Sensitivity of various variables can be observed and trade offs between them compared. Cause and effect relationships can be graphed and general trends can be learned.

BFORM does not consider the possibility of VERTREP. However, the operator could account for this by increasing the transfer rates of several commodities to simulate the effects. Combatants could also use sortie rates greater than zero to simulate the consumption of JP-5 for HIFR.

III. ANALYTICAL OBJECTIVES AND BASIC ASSUMPTIONS

The analytical objectives of this effort are to determine the trade offs among two methods of UNREP (delivery boy and service station), different battle group speeds of advance (SOA), different UNREP speeds, and the various UNREP flag levels which signal the commodity level for which UNREP is considered appropriate. A central question is the degree of difference between the two principle types of UNREP when measured by the average on station time (AST), defined on page 21, of the combatants. Depending on the operational tempo, the CWC can decide if the delivery boy UNREP method is justifiable, considering the threat, rather than the safer service station method of delivery.

If the delivery boy method of UNREP is used in order to maintain a high AST, certain risks are entailed. By doing this kind of UNREP, the AOE (vital asset) will be exposed miles away from the center of the formation. The AOE will be involved in UNREPs with only one combatant at a time. Efficient use of the AOE would suggest allowing simultaneous UNREPs. However the doubling up of UNREPs on the outer edge of the screen is even less desireable.

For the purposes of this study the CV and the ships of the inner screen maintained an average speed of 3 knots greater than SOA throughout the simulation run to simulate the needed speed and with that the fuel consumption to sustain flight operations. Ships of the outer screen maintained an average speed of 1 knot greater than SOA for the purpose of station keeping, patrolling, etc.

The following is a list of assumptions imposed by the model BFORM.

- DFM consumption rates for the combatants are only considered for 14 - 30 knots, in 2 knot increments.

- Station ship does not expend fuel except in transfers to other ships.

- All combatants transit at maximum speed when regaining station or departing station to rendezvous for UNREP[1].

- Replenishment ship travels at top speed when going to UNREP with a combatant in the Delivery Boy method, which is set at 26 knots for an AOE.

- 20 minutes is added to each UNREP time for approaching, rigging and unrigging. The choice of 20 minutes is explained on page 8.

- In the delivery boy mode, the station ship will remain at the relative position upon completion of the UNREP. It will stay there and steam at the indicated SOA until instructed to rendezvous with another combatant by the scheduling algorithm.

- No change to battle group base course is made during the simulation run.

- During any given simulation run, all commodity and ship priorities are constant.

- UNREP transfer rates will be reduced if the user inputs a weather event with sea states greater than 3.

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[1]The program BFORM will use the maximum speed available from the Ship's Characteristics file. The author limited all combatants specifically to a maximum speed of 30 knots because of this. Accordingly their fuel consumption will be for 30 knots when transitting either to or returning from UNREP.

At sea state 4, transfer is reduced by one third. At sea state 5 and above, no UNREPs will be scheduled.

- If no weather event is entered by the user, then sea state 1 is assumed.

The following is a list of assumptions imposed by the author.

- A 10 day transit.
- No weather conditions were considered, therefore all UNREPs were conducted on base course.
- UNREP speed will not be faster than the given SOA.
- The only commodities considered were DFM and JP-5.
- Only the CV consumed appreciable amounts of JP-5.
- JP-5 consumption was 2.4 kgal per sortie, and 75 sorties per day for the 10 day transit.
- All combatants were given a patrol radius of 0.1 nautical miles in order to ascertain time off station with precision.
- Combatants in the inner screen steam on the average at three knots above SOA. This includes the CV.
- Combatants in the outer screen steam at one knot above SOA.
- Transfer rates for the combatants were as follows[2]:

Ship	DFM	JP-5
CV	250 kgal/hour	250 kgal/hour
CG47	200 kgal/hour	
DD/DDG/CG26	180 kgal/hour	
FFG	90 kgal/hour	

- DFM consumed by the AOE was not considered.

[2]Transfer rates were obtained from a concurrent analytical study of actual fleet data. It is believed that these values represent transfer rates more realistically then those given in NWP-14.

- Threat axis of 000 degrees relative, for the purpose of ship placement.

- Shuttle lifts will be available[3].

- The time required and the effects of transferring DFM from a shuttle ship to the AOE were not considered. This is further discussed on page 22.

- Flag levels, which initiate the need for an UNREP, are varied over three levels 50%, 65%, and 80%, however the 65% flag was used for the design. Refer to page 27.

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[3]For a 10 day transit, present day capacity of an AOE is insufficient to support even the smallest battle group considered in this study under all operating conditions. Therefore, to enable the model to run for each formation design it was necessary to increase DFM capacity on the AOE. This hypothetical capacity was set at 10,000,000 gallons.

IV. EXPERIMENTAL DESIGN

For the experimental design, three notional battle groups were constructed for the purpose of a ten day transit. Table 1 lists the ships assigned to the battle groups. Battle groups A, B, and C represent a low, reasonable, and high mix of combatants respectfully [Ref. 6]. All formation groups contained one conventional aircraft carrier and one AOE (non combatant). Ship characteristics were extracted from NWP 11-1B and entered into the model BFORM.

TABLE 1. NOTIONAL BATTLE GROUPS

Group A		Group B		Group C	
1	AOE	1	AOE	1	AOE
1	CV 63	1	CV 63	1	CV 63
1	CG 47	1	CG 47	2	CG 47
1	DDG 51	2	DDG 51	2	DDG 51
2	DD 96	3	DD 963	3	DD 963
1	FFG 7	2	FFG 7	2	FFG 7
				2	CG 26
6 COMBATANTS		9 COMBATANTS		12 COMBATANTS	

No single document was found to provide ship placement within the formation for a generic low threat transit. The figures in Appendix A provide the placement for the combatants used. Within each formation the inner and outer screens were placed 10 and 50 nautical miles respectively from formation center. Based on several interviews with acknowledged experts in the field of battle group steaming profiles, it is believed that these represent generic and reasonable formations. Ship positions were considered for effects of convergence zones and electromagnetic radiation, and placed to reduce interference between combatants, and at the same time provide adequate protection. A threat axis of 000 degrees relative was assumed for purposes of ship placement. All combatants are on course 000.

One measure of effectiveness (MOE) developed was the average on station time (AST) for the battle group as a whole. AST being defined as:

$$AST = 1 - \frac{\text{Total time off Station}}{\text{Total time}}$$

This measures the time the battle group, on the average, spent on station, i.e., not involved with UNREP.

Another measure considered was average minimum commodity level reached by the battle group. Due to the starting levels, ship placement, and the flag level set to initiate UNREP, the minimum levels reached for the duration of the simulation run for each commodity could be recorded and averaged for the battle group. This could aid the CWC in his decisions. Knowing or having a good idea what the minimum level reached by his combatants would be, the CWC could determine if a delivery boy or service station UNREP method was sufficient or adequate.

Both of these measures exclude the AOE data. It is assumed that a shuttle lift will be available on demand to top off the AOE. Therefore AOE figures are not considered as factors in the MOEs. All UNREPs are conducted either by delivery boy or service station method. It is assumed that either MOE could be maximized by using one of these resupply methods but not both. What this means is that in order to obtain the maximum AST you would use a delivery boy method of UNREP. However, this would cause the combatants to reach a lower level of a commodity due to the time delay in waiting for the AOE to arrive at the combatants station.

Another important fact to consider is the duration of a single UNREP. What is the maximum off station time for a single unit? Can CWC afford to have a unit from the outer screen off station, involved with UNREP, say up to 4 hours at one time? As a third measure, the average maximum off station time for the battle group will be collected and evaluated.

One question we answer at the outset is, what to assume as the starting levels of DFM and JP-5 for the combatants. Initial fuel levels were allowed to varied from 100 down to 55 percent. The flag level to initiated the need for an UNREP was set at 80 percent. The following analysis of the starting fuel levels is provided to support the selected initial conditions. Formation A was used in a ten day simulation run. This formation proceeded at an SOA of 13 knots and had an UNREP speed of 12 knots. Neither the upper bound nor the lower bound would be chosen, however this would give an area in which an appropriate starting level could be drawn. Using three different starting fuel levels, 55%, 80%, and 100%, Table 2 provides the recorded data of the day by day account of AST. Figure 2 provides a graph of the recorded data for the three levels using the delivery boy method of UNREP.

From Figure 2 it is clear that the AST settles out rather quickly and maintains about some constant reasonable well. It is felt that whether this sustained constant AST is 97% or 94% for either method of delivery is immaterial; however, the fact that it does settle out is important. Obviously not all ships of a battle group will start at 100% fuel level and just as obviously not all will start at 55%. From this an average starting fuel level was chosen, which was 80%. Table 1 of Appendix B lists the chosen starting DFM levels for each combatant within each battle formation.

TABLE 2. INITIAL STARTING DFM LEVELS FOR ALL COMBATANTS

DAYS	55% D / S	80% D / S	100% D / S
1	.9015 / .8210	.9470 / .8669	1.0000 /1.0000
2	.9508 / .9105	.9735 / .9334	.9993 / .9980
3	.9609 / .9324	.9761 / .9466	.9925 / .9875
4	.9671 / .9231	.9766 / .9345	.9821 / .9664
5	.9670 / .9337	.9761 / .9429	.9822 / .9695
6	.9725 / .9448	.9800 / .9499	.9901 / .9705
7	.9727 / .9364	.9792 / .9410	.9815 / .9598
8	.9700 / .9425	.9791 / .9482	.9829 / .9635
9	.9743 / .9457	.9793 / .9496	.9827 / .9644
10	.9761 / .9427	.9807 / .9472	.9837 / .9593

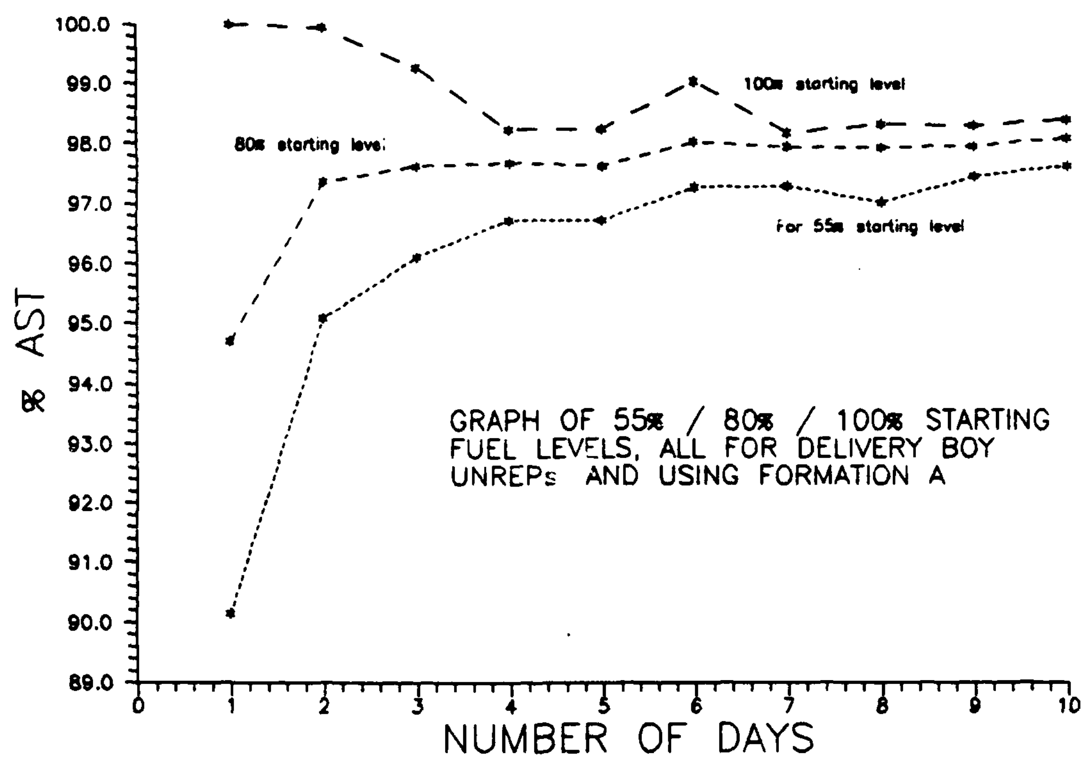

Figure 2. Starting Fuel Levels

It is understood that not all ships will start at the same fuel level. Figure 3 compares AST vs duration of the run for formation A using the selected starting DFM levels given in Table 3 of Appendix B with that of all combatants starting at 80%. Collectively the combatants of the battle groups will have an average initial fuel level of 80% for the remainder of the design.

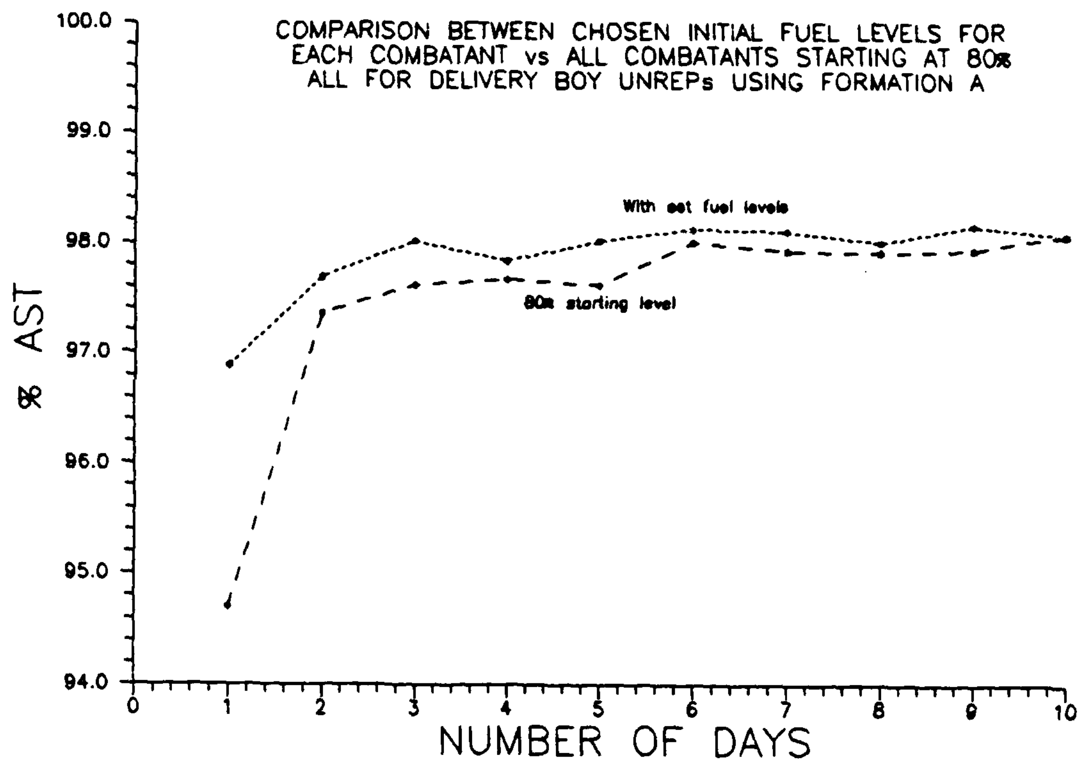

Figure 3. Comparison Between Initial Fuel Levels

Each battle group conducted a ten day transit with the set starting fuel levels given in Table 3 of Appendix B. After setting the initial fuel levels, a comparison between three set flag levels for each battle group was considered.

After an analysis of these results, one flag level was chosen for the rest of the design.

Now that the starting fuel levels and a set flag level have been chosen, each battle group will preform a series of ten day transits using the two UNREP methods. The series of runs will be conducted varying the speed of advance from 13-21 knots in two knot increments. UNREP speed will vary over the range of 12-20 knots, also in two knot increments. Data collected from each run will be the average battle group on station time, total time AOE was involved in UNREP, the average battle group maximum off station time, average mean DFM level, and the minimum battle group DFM level reached during the run.

V. ANALYSIS

A. ANALYSIS OF THREE FLAG LEVELS

Three flag level settings were used with the starting fuel levels obtained from the Chapter IV. The flag levels used were 50, 65, and 80 percent. The flag level queues the scheduling algorithm to initiate an UNREP. Each formation started with an initial fuel level average of 80%. A series of 10 day transits were conducted for each individual level within the model. Using the three upper threshold levels (flag levels) data were collected from the three runs using a delivery boy method of UNREP. The figures in Appendix C show the results of those runs. For each run an SOA of 13 knots and an UNREP speed of 12 knots was used. A plot of AST vs duration of the run in days clearly shows a small change in AST given the three flag levels. This will consistently hold true when the battle groups are not over-taxed with logistics and when comparing the same method of UNREP with each flag level.

With the flag set at 80%, 34 UNREPs were generated using formation B, while 40 were generated using formation C. This gives an average of 3.4 and 4.0 UNREPs per day for the 10 day transit. With an SOA of 13 knots and an UNREP speed of 12 knots, this will lead to least fuel demanding conditions considered within the design. An average of 3.4 and

4.0 UNREPs per day is very demanding for the AOE even under the most favorable conditions, so the 80% flag was removed from further consideration.

Left with the two alternatives, i.e., 50 and 65 percent, and operating under the same conditions, the difference between the ten day mean fuel levels aboard the combatants was approximately 10%. This means that with a flag level set at 65% vice 50%, the average fuel level aboard the combatants within formation B throughout the ten day transit was 10% higher. This would sustain the ships of this formation for roughly 1.13 days longer at a sprint of say 20 knots. Comparing this kind of additional sustainability without affecting AST by an appreciable amount (see the last figure of Appendix C) a flag level of 65% was selected for the rest of the design.

Additional insight is provided for a decision maker pertaining to AST for the CV vice AST for the battle group as a whole. Understanding the CV as the critical element of the battle group, the AST for the CV needs to be clearly displayed. By removing the off station time of the CV from the rest of the battle group and plotting the CV's AST vs duration of the simulation run this would provide a clear picture. Again, operating under the same conditions as above, Figure 4 shows a comparison of formation B using a delivery boy method of UNREP for battle group AST, battle group AST excluding the CV and AST for just the CV. The important finding to conclude from this graph is that the average AST for the whole battle group will be on the order of 2 percent higher than that for the CV when using a delivery boy method of UNREP. Another way to think of this is that it will take, on the average, twice as much time for

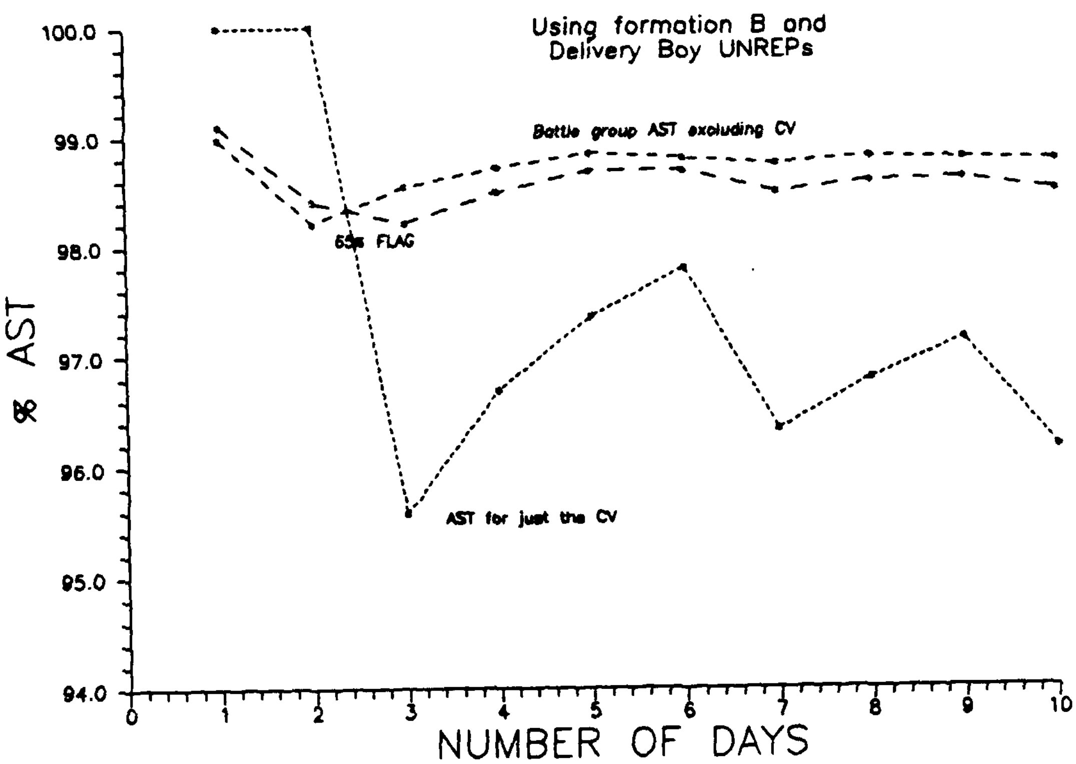

Figure 4. Delivery Boy AST For CV

the CV to be involved in UNREP as compared to the average UNREP time for the rest of the battle group when using the delivery boy method. However, when using the service station method of UNREP, AST for the CV is approximately the same as for the whole formation which is very close to the AST for the formation excluding the CV (see Figure 5).

B. ANALYSIS OF AST vs SOA

With initial fuel levels set and with an appropriate flag level selected, the three formations were used in ten day transits. The UNREP speed was varied between 12 and 20 knots in 2 knot increments. The results from the three formations are plotted in Figures 6, 7, and 8. This clearly shows that the delivery boy method of UNREP will give the best average on station time for the battle group.

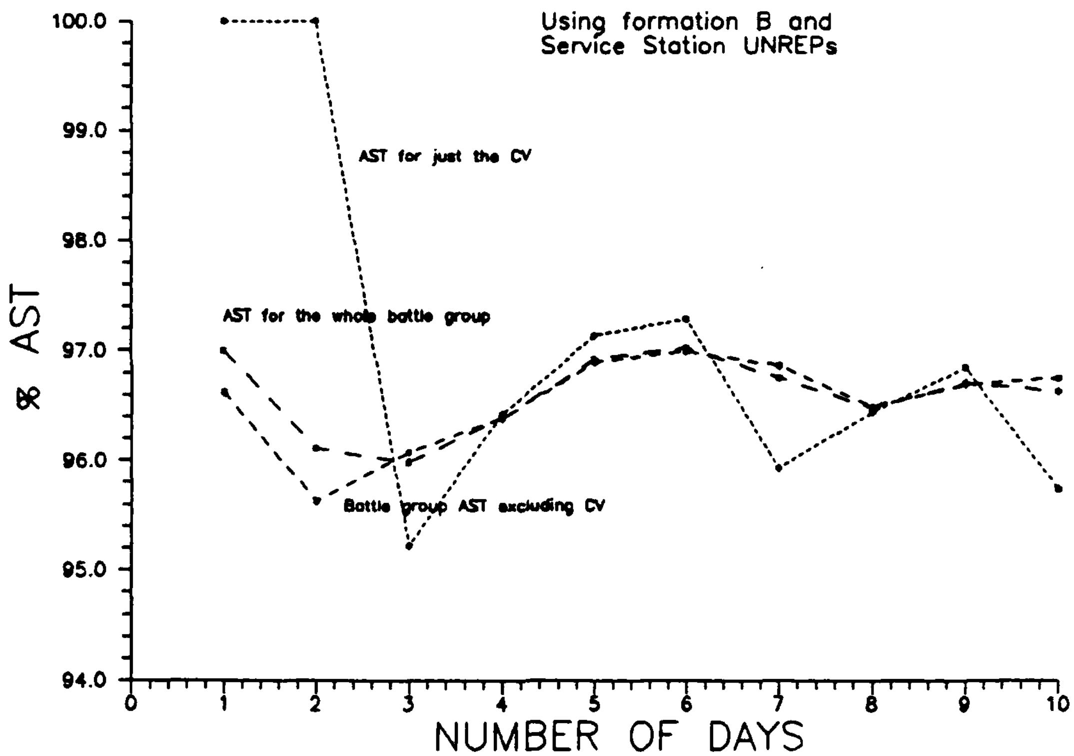

Figure 5. Service Station AST For CV

The uppermost small dashed line in each figure represents an upper bound. This line shows the AST for the battle group when only considering the time required to conduct the UNREP, i.e., time required to transfer fuel plus 20 minutes.

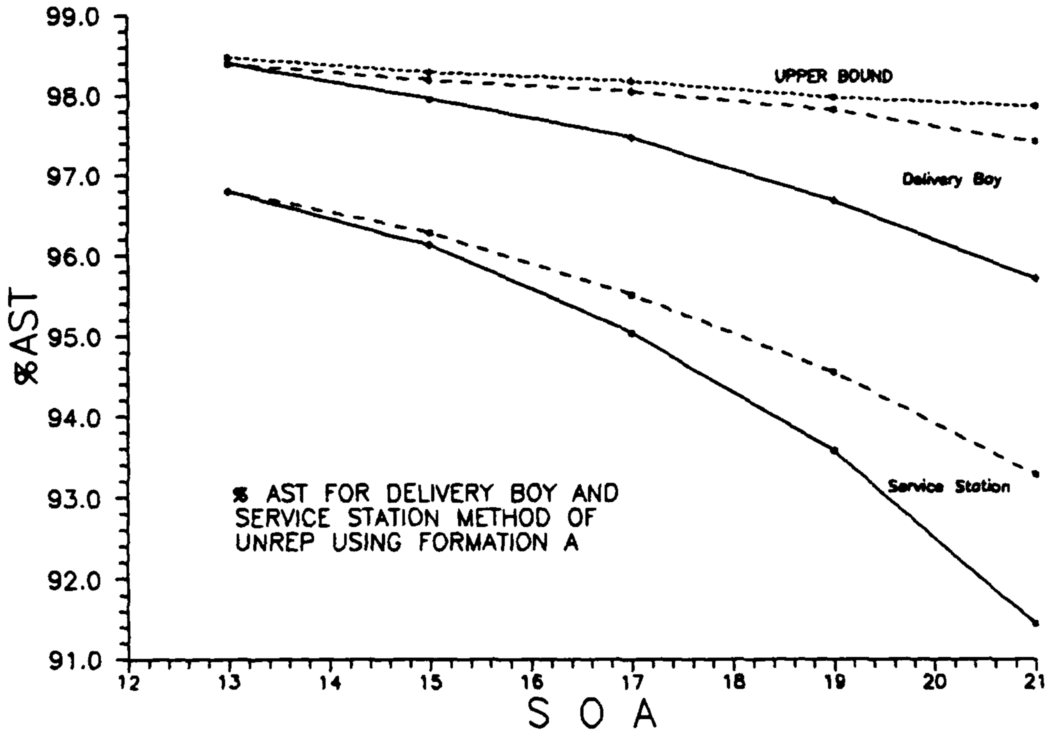

Figure 6. AST vs SOA For Formation A

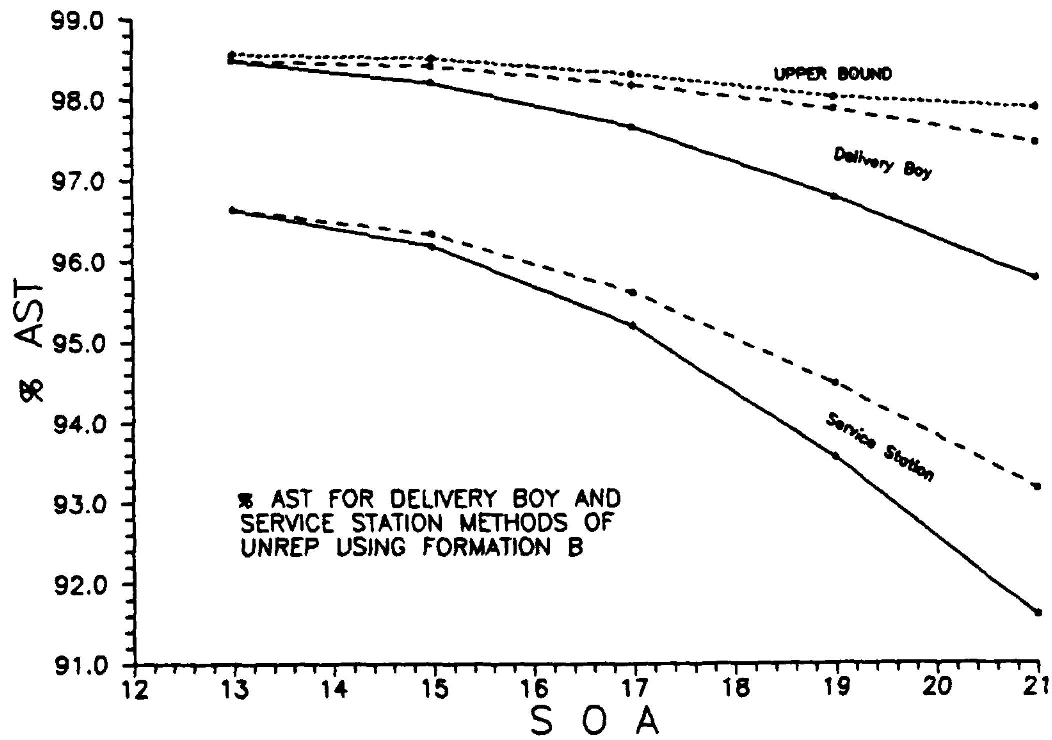

Figure 7. AST vs SOA For Formation B

Only the delivery boy upper bound is plotted, because the service station method has very similar results, except at the upper range of SOA it starts to fall. It drops approximately 2 tenths of a percent at 21 knots. It is impossible for the battle group to achieve a higher AST then this upper bound when operating under the assumed transfer rates given in Chapter III, independent of the method of UNREP, SOA, or UNREP speed.

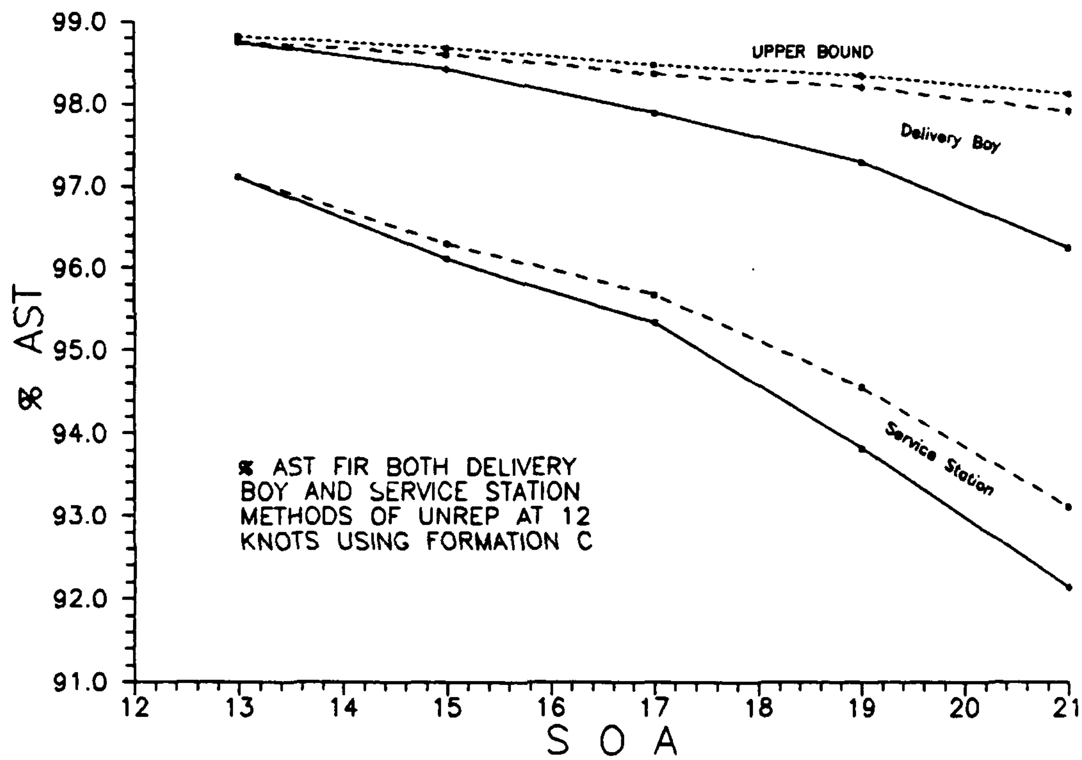

Figure 8. AST vs SOA For Formation C

In each figure both the delivery boy and service station results are plotted. For each method of UNREP the lower solid line represents AST using a 12 knot UNREP speed. The upper large dashed line represents an UNREP speed which is one knot less than the given SOA. As one would expect the higher the UNREP speed with respect to SOA the better the AST. It is assumed that a battle group would not UNREP faster than the given SOA.

Laying Figures 6, 7, and 8, over one another reveals an interesting trend. The trend for AST to decrease as SOA increases appears to be independent of the formation used. Both delivery boy and service station AST follow the same basic trends. The reader should keep in mind that these are notational battle groups, and formation placement is generic. As should be expected because fuel consumption is non-linear, as SOA increases the AST for the battle group starts to fall off rapidly. Also as SOA increases the benefits of a delivery boy method of UNREP also increase with SOA as compared to the service station method.

C. ANALYSIS OF UNREP SPEED vs SOA

The purpose of this study was to analyze the trade offs between the two methods of UNREP. With this in mind a plot was made of AST for a delivery boy method of UNREP vs AST for a service station method. Figure 9 shows the results of delivery boy AST vs service station AST for the three formations used. Using the method of least squares, best fit lines were plotted for an UNREP speed set at 12 knots, which is the lower small dashed line, and for an UNREP speed one

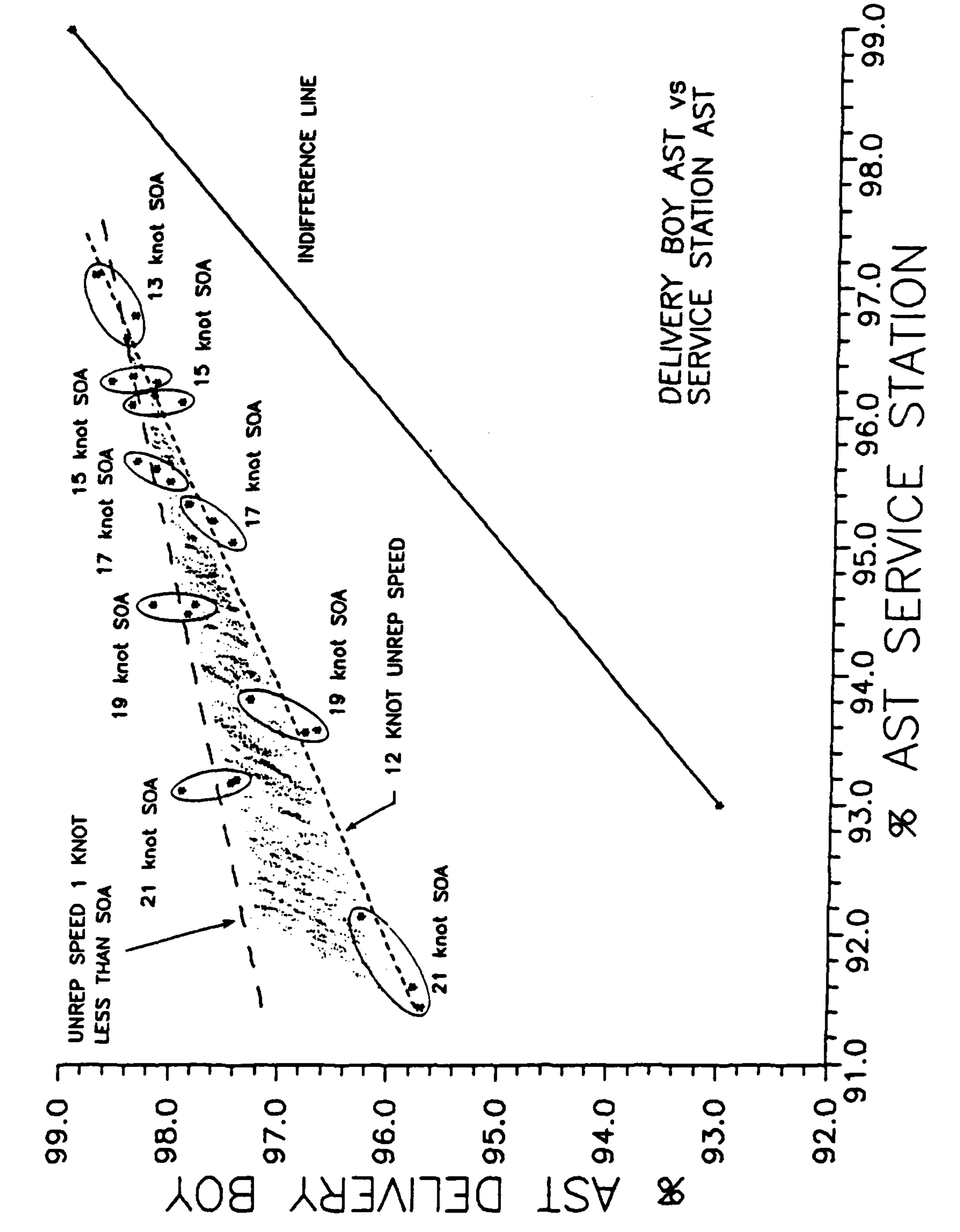

Figure 9. Delivery Boy AST vs Service Station AST

knot less than SOA, which is the upper large dashed line. The results from all three formations using the same SOA are circled, and the results from the three formations using the same UNREP speed are used to fit each best fit line.

The shaded cone shaped region between the two best fit lines represents an area in which the CWC could expect the results to fall when UNREP speed is varied between 12 and 20 knots using similar formations. The independent line to the right represents an indifference line, meaning one would be indifferent between the two methods of UNREP because they provide the same AST. In all cases the preferred method of UNREP did not change when UNREP speeds was varied, independent of SOA or formation used. Figure 9 shows that the higher the SOA the more a delivery boy method of UNREP is preferred in order to maintain a high AST.

It is clear from Figures 6, 7, and 8 that by increasing the UNREP speed the CWC would be able to maintain a higher level of AST. What may not be clear is why the service station method of UNREP does not have the same advantage at increased UNREP speed as does the delivery boy method. Figure 10 graphs the percent of time off station due to transit as distinct from time off station due to the UNREP itself. For the service station method the majority of the off station time for the combatants is always due to their transit to and from the AOE. It can be seen in Figure 10 that when increasing UNREP speed from 12 knots to one knot less than SOA, comparatively little was gained for the service station method. For delivery boy at slow SOA only a small percentage of off station time was due to transit time. As SOA increases, unless UNREP speed is increased correspondingly, a significant increase in off station time due to transit time will occur.

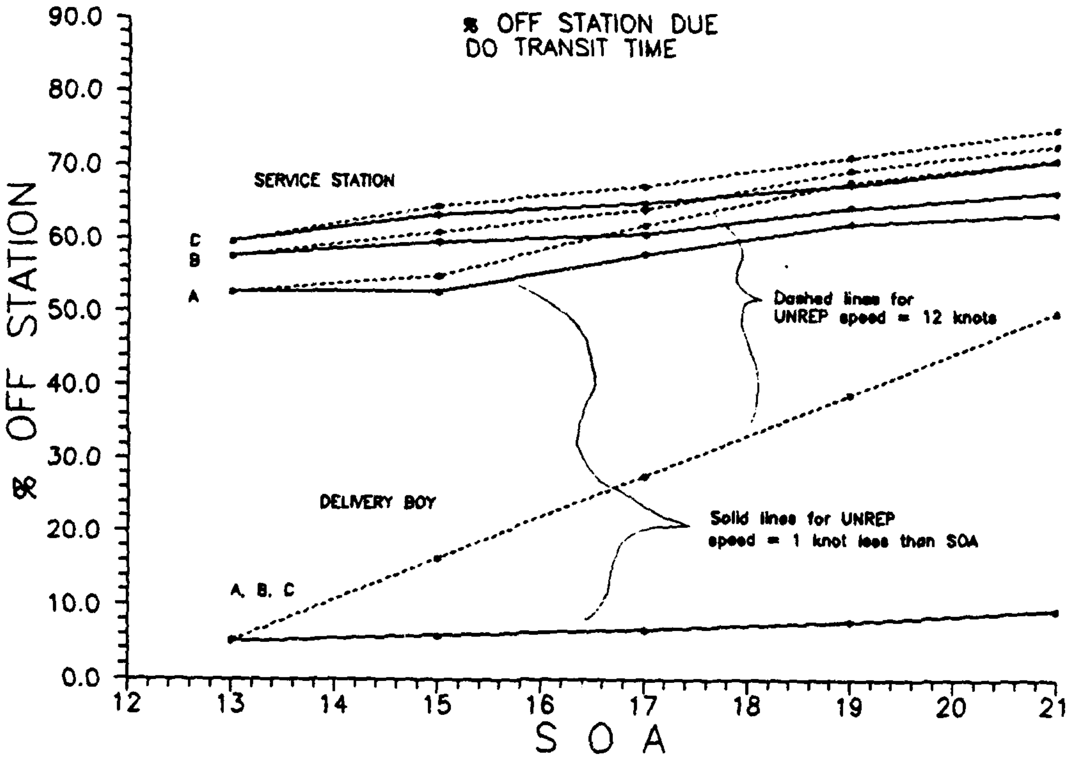

Figure 10. Off Station Time Due to Transit

D. ANALYSIS OF AOE IDLE TIME

The fact that AST for both methods of UNREP using formation C was comparable to that obtained using formation A and B lead to an expectation that commodity levels were significantly lower due to the fact that the AOE had more ships to manage and the long transit times. Naturally formation C will be a larger burden on the AOE when using the delivery boy method.

Mean commodity levels and the minimum level reached for the battle groups were analyzed. Figure 11 is a plot of the average battle group mean commodity level, i.e., the aggregate average for all combatants in the battle group, with respect to SOA for the three formations[4]. This graph shows very little difference between the three formations except at an SOA of 21 knots. Figure 12 plots the minimum commodity levels reached by any one ship in the battle group and was plotted by connecting the minimum levels obtained from the output of BFORM for each selected SOA. For each run, as SOA was increased, the same ship did not necessarily produce the minimum level. Figure 12 shows very little difference between the three formations except at 21 knots. The solid flat line in Figure 12 is where the flag is set which initiates the scheduling algorithm to initiate an UNREP. In all cases, except for an SOA of 21 knots, the values for the average battle group mean commodity level and the minimum commodity level reached do not vary by any significant amount between formations.

[4]Remembering that DFM and JP-5 are the only commodities monitored.

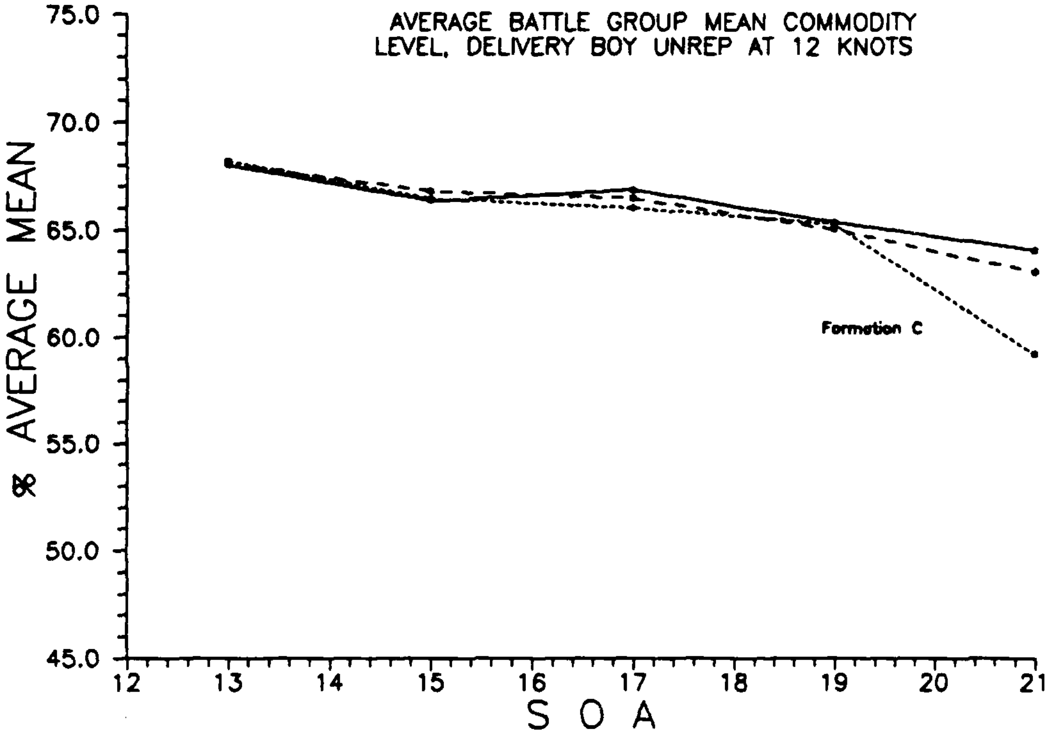

Figure 11. Average Battle Group Mean Commodity Levels

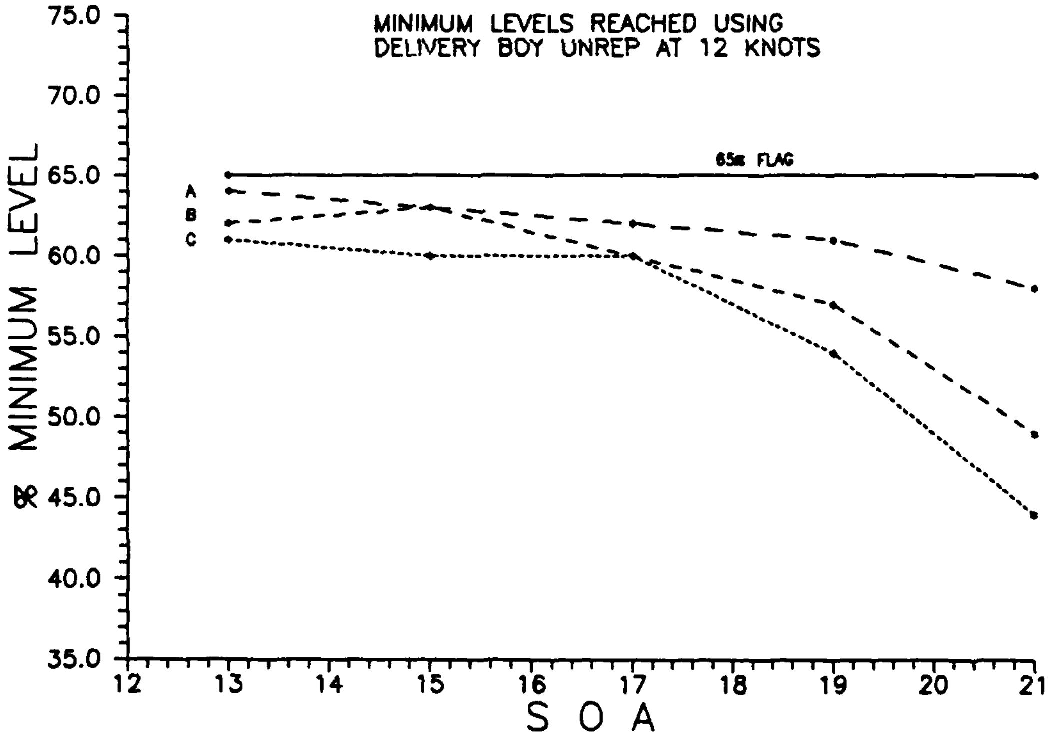

Figure 12. Minimum Levels Reached

For an SOA of 21 knots it is not clear whether formation C produced significantly different average mean commodity levels or minimum levels reached from the other two formations. The delivery boy method of UNREP and the use of a 12 knot UNREP speed with an SOA of 21 knots made this the most demanding case to maintain commodity levels. This is because the combatants are required to stay on station in the formation and wait for the AOE to arrive.

An investigation as to the cause led to an analysis of the idle time for the AOE. Idle time for the AOE is defined as the time the AOE was not involved in UNREP, in transit to UNREP, or in transit from UNREP. A point which needs to be made here is that the AOE will make a transit after UNREP only for the service station method to regain its assigned station. After a delivery boy UNREP the AOE will steam along at the indicated SOA from the point at which the UNREP was completed. Only when the scheduling algorithm cues the next ship in need of UNREP will the AOE transit to that ship's position to conduct an UNREP.

In Figure 13 idle time for the AOE is plotted as a percentage of the total time available to the AOE, 240 hours (24hr / day x 10 days). It may be deduced from the percentage plot of Figure 13 that the AOE only had 21.47 hours of free time when using formation C and a delivery boy method of UNREP at 21 knots SOA.

An inspection of the data collected in the output of BFORM showed that there was only one point in which sufficient time was available for a console (when a shuttle ship transfers its commodities to the station ship) under the conditions just stated. This occurred at day 5.5 in the

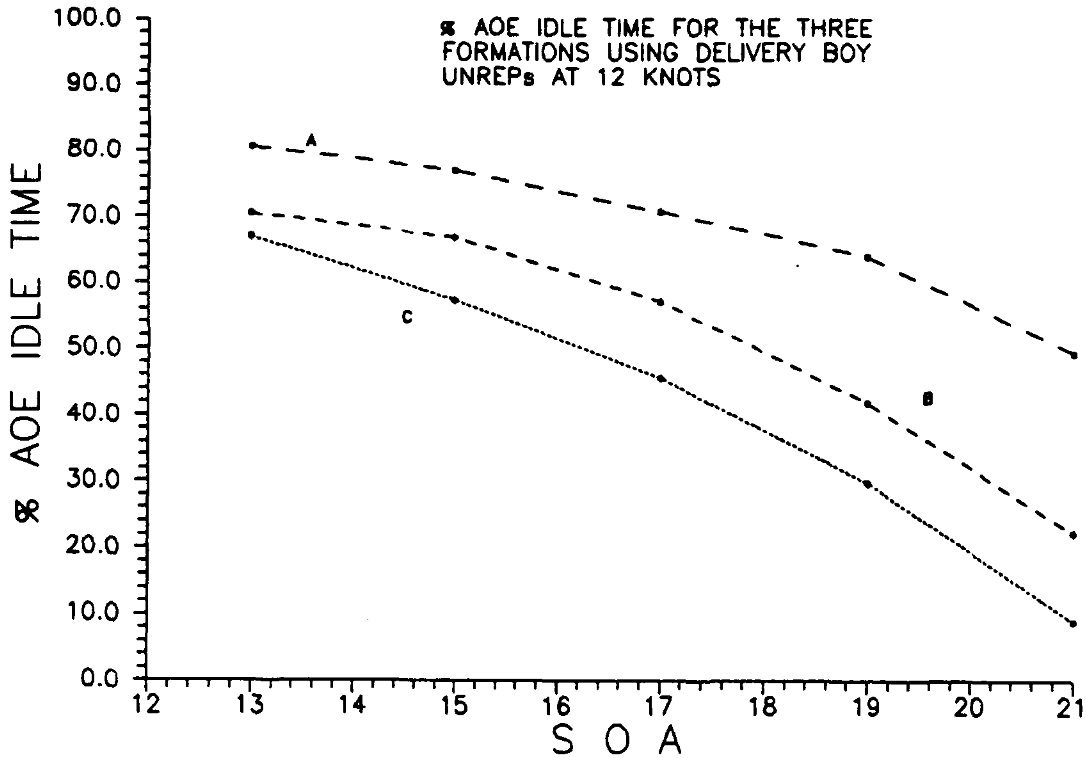

Figure 13. AOE Idle Time

simulation run. The AOE has sufficient fuel capacity to sustain this formation under this OP TEMPO for approximately 6.6 days.

The percentage of idle time for the AOE appears in an intuitively appealing manner. As expected, as the number of ships increase within the formation, the idle time for the

AOE decreases. The plot for formation C does not appear to deviate significantly from the other two formations.

E. ANALYSIS OF OPENING UP THE FORMATION

Formations A, B, and C were opened up to simulate extended formations. These extended formations used the same relative positions as in the base case, but with the outer screen placed 130 nautical miles from formation center vice 50 and the inner screen placed 30 nautical miles from formation center vice 10.

Figure 14 graphs the results of the simulation run using both delivery boy and service station methods at a 12 knot UNREP speed. The general trends observed earlier still apply. The AST maintained by the battle group for the delivery boy method of UNREP using the extended formation compares almost identical with that of the base formations. As expected for the service station method of UNREP, AST fell drastically due to the transit times for the combatants.

Figures 15 and 16 plot average mean commodity levels and the minimum levels reached, respectively, for both the delivery boy and service station methods of UNREP. Although the extended formations maintained high AST under the delivery boy method, what is not seen in Figure 14 is that combatants suffer, i.e., reached much lower levels of fuel at the upper range of SOA. This can be easily seen when comparing Figure 16 with that of Figure 12.

Figure 17 plots the AOE idle time for the delivery boy method using all three formations. When using formation A the AOE was able to maintain sufficient idle time to console around day 5 even for an SOA of 21 knots using either method of UNREP. However, in formation B the AOE could sustain this posture at an SOA of 17 knots, but could not at an SOA of 19 knots when using the delivery boy method. For the service station method, formation B was able to maintain 21

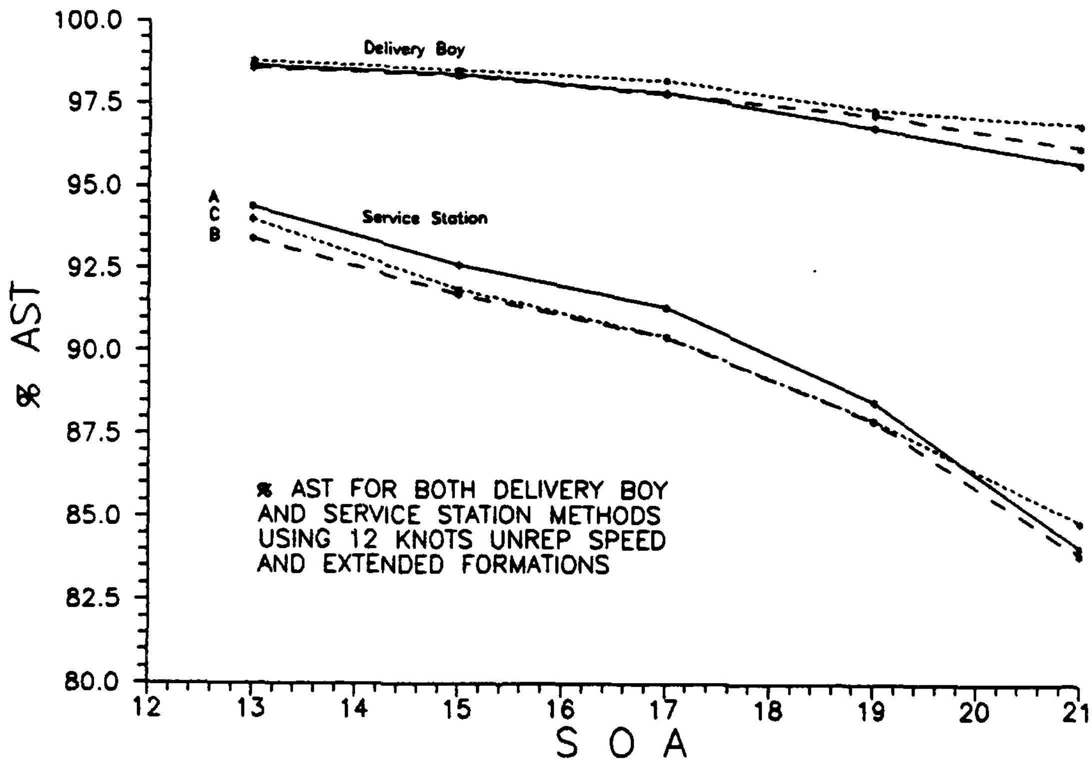

Figure 14. AST vs SOA Extended Formation

knots SOA, but could not provide sufficient AOE idle time to console at 21 knots SOA. When using formation C things got even worse. This formation was able to sustain sufficient

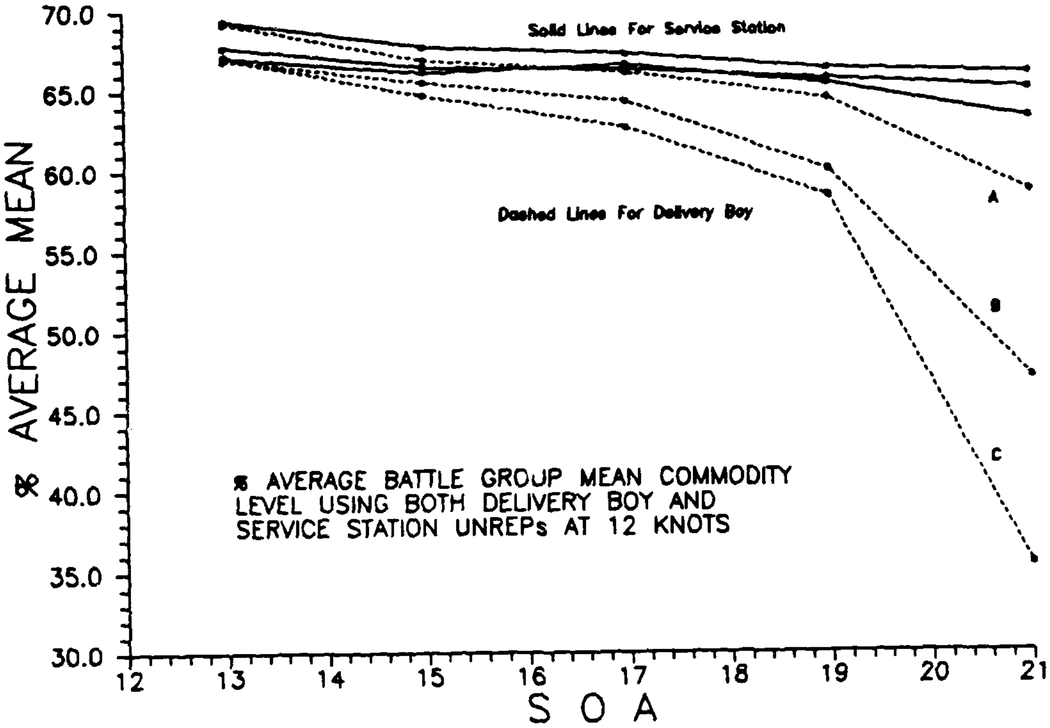

Figure 15. Average Mean Commodity Extended Formation

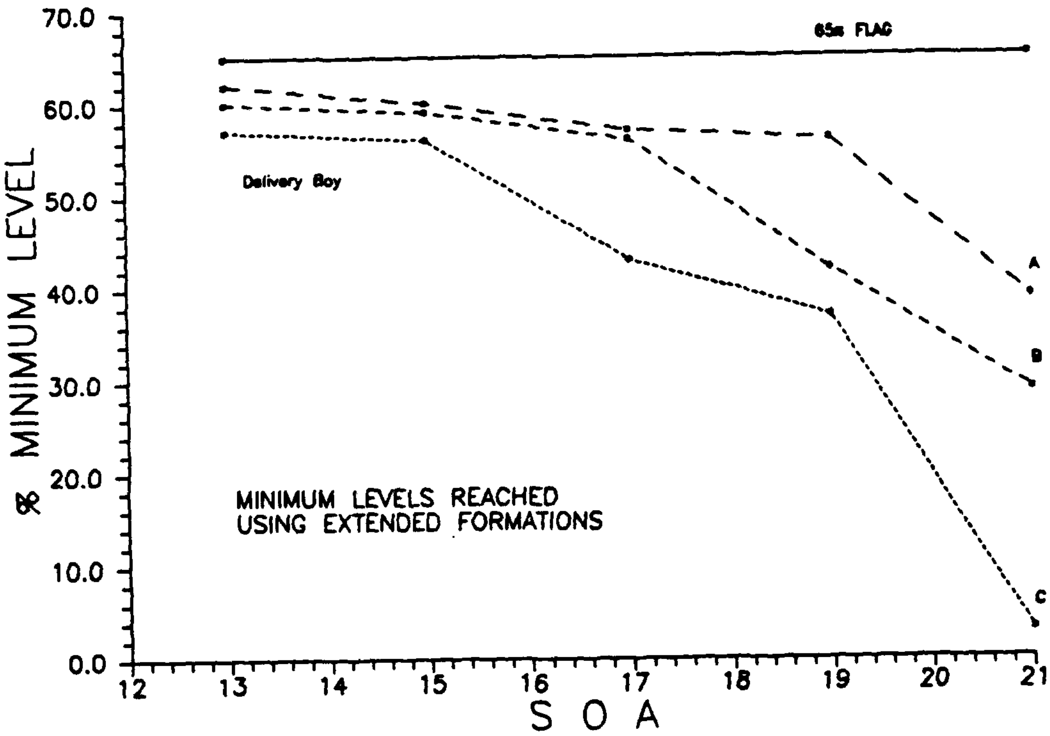

Figure 16. Minimum Levels Reached Extended Formation

idle time for the AOE to console when using 15 knots SOA for delivery boy method and 17 knots SOA for service station method. However it could not provide this posture at 17 knots SOA for delivery boy method and 19 knots SOA for service station method.

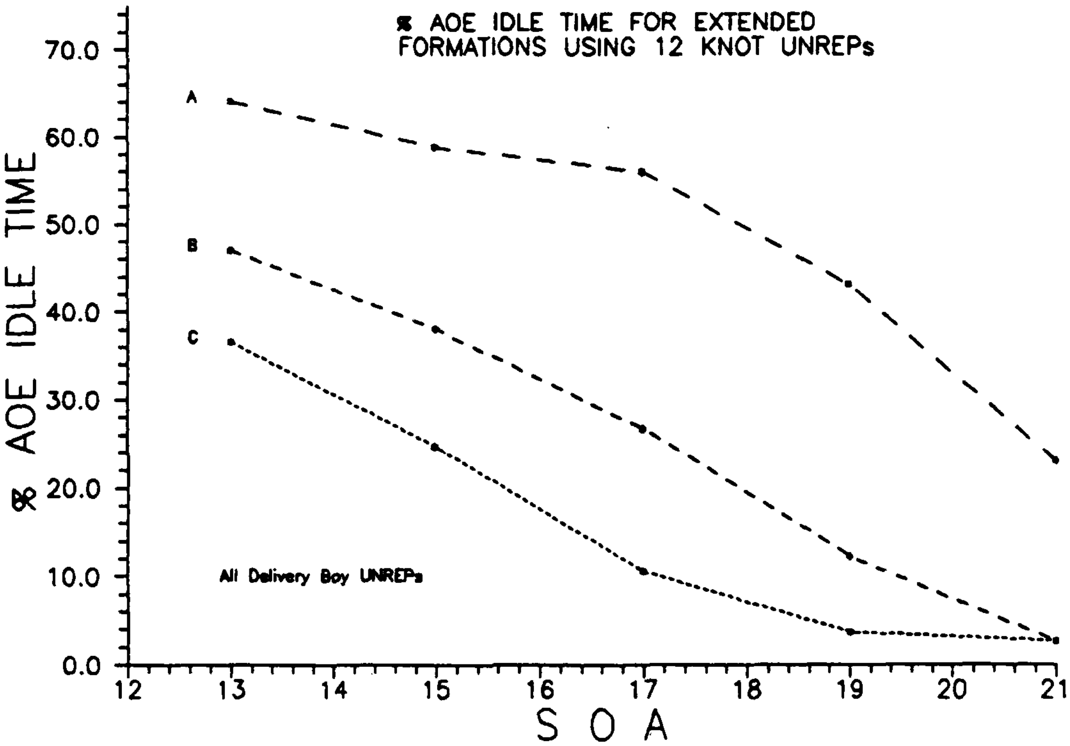

Figure 17. AOE Idle Time Extended Formation

The program has a few hours at the start of each simulation run where the AOE is idle, this is due to the fact that no ships start the simulation at or below a 65% fuel level. Therefore, as seen in Figure 17 the plots for formation B and C start to level off down in the range of 5% AOE idle time. In other words for formation C the AOE is essentially busy continuously above 17 knots, and the queue of ships waiting to fuel is building up without end. The same situation occurs for formation B at 21 knots. As expected, when using formation B and C in the delivery boy mode in the upper range of SOA, once the AOE started UNREPs it never caught up, i.e., it always had some ship waiting to be refueled. The ships never ran out of fuel during the ten day transit, although a few did reach some unacceptably low levels.

VI. RESULTS AND CONCLUSIONS

A. METHOD OF UNREP

One of the OTC's major decisions is between being continuously topped off for battle verses the degradation of readiness due to screening ships off station or the exposure of the UNREP ship when the delivery boy makes its rounds. The tactical commander must also decide between the service station and delivery boy method of UNREP or something between the two, a possibility we have not analyzed. Measuring the time the battle group, on the average, spends on station (AST) is one means of measuring the effectiveness of the battle group. Trying to maintain a "Ready" battle force by keeping his units topped off at 80% will degrade the screen effectiveness and overtax personnel and equipment.

In Figures 6, 7, 8, and 14 we readily see how much better in AST the delivery boy method is than the service station method. How much AST the decision maker must sacrifice for a service station method will depend on the UNREP speed, SOA, the number of combatants within the formation, and formation dispersion. Figure 9 shows that as SOA increases the preferred method becomes even more preferred, i.e., moves further from the indifference line. As SOA increases the AST lost using a delivery boy method is smaller as compared to AST lost for a service station method.

The additional benefit in AST due to increasing UNREP speed is higher for a delivery boy than for a service station method. Relative to the same SOA, this is due to the large amounts of time involved in the total transit for the combatants using the service station method. This can be seen in Figure 10, which shows, as UNREP speed is increased from 12 knots to one knot less than SOA, the additional decrease in the percentage of off station time due to transit is overwhelmed by the large transit time under the service station method.

In order for the AOE to meet combatant refueling demands and at the same time have sufficient time to refuel from a shuttle ship, a certain level of AOE idle time is required. More time is required to conduct delivery boy UNREPs vice service station UNREPs. Idle time for the AOE is dependent on the number of ships in the formation and range of the units from formation center. It was found that the AOE could provide the required refueling services given that it had approximately 15% or more idle time.

The AOE was able to serve formation A (6 ships) under all operating conditions, even the extended formation, and maintained commodity levels relatively close to the set flag. Using formation B (9 ships) however, the AOE could provide the required services when screen formation was set at 50 nm. It could not for the extended formation (at 130 nm) above 19 knots SOA. A further constraint was observed with formation C (12 ships). The AOE could not provide the extended formation above 17 knots SOA. As seen in Figures 16 and 17, extremely low fuel levels in the combatants and the AOE idle time down in the range of 5% clearly show that the AOE is incapable of providing for more than 9 combatants in an extended formation when required to maintain an SOA of 19 to 21 knots for any extended period of time. It was observed that the AOE could provide an extended formation for short periods of time.

Under these extended formations it was not uncommon to have AOE transit times in excess of 15 hours, and even up to 24 hours when using an SOA of 21 knots. When using the close-in formation transit times seldom exceeded 10 hours. The scheduling algorithm comes into play here. For instance if a ship on the outer screen enters into the queue for UNREP and the AOE has another ship enter the queue before the AOE starts its transit to the outer screen, due to the scheduling algorithm, then typically the closer ship will be UNREPed first. The major outcome of this is that very seldom will the AOE make a transit between combatants on opposite ends of the screen. Therefore transit times are not as long as would otherwise be expected.

As a tactical aid for a decision maker, the analysis of the results of BFORM provides some insight into the trade offs between the methods of UNREP and the desired SOA. Considering the mission of the battle group, training, surveillance, or intelligence gathering, all of which typically fall under the heading of "peace time" operations, a CWC may want to use a delivery boy method of UNREP knowing that this method will maximize AST. Within a high threat environment, a service station method provides the best protection for the AOE. Consideration must be given to this vital asset, considering that a battle group in the extended formation B could not operate for long over 6 days without having the majority of its combatants running out of fuel using an SOA of just 19 knots.

Effective use of the AOE prompts the use of simultaneous UNREPs. Consolidating UNREP evolutions will ease the overall work load. Battle group endurance is directly related to the staying power of the AOE. The AOE delivers roughly 60% of its cargo to the CV, which is another reason to keep the AOE in the vicinity of the CV.

B. THE PROGRAM BFORM

The program BFORM will abort if the user tries to use an UNREP speed equal to that of the SOA. This is why in the analysis an UNREP speed of at least one knot less then SOA was chosen. BFORM also will abort if SOA is set equal to the maximum speed of the station ship. The program will however run if the UNREP speed is set faster than the however run if the UNREP speed is set faster than the maximum speed of the station ship.

The program is flexible and allows the user to model realistic situations. The operator can use different flag levels for the different combatants within the formation, depending on the units' priority and mission. The program should be improved in three ways; it should include the fuel usage of the station ship, it should have the station ship return to its assigned station after a delivery boy method of UNREP instead of staying in the vicinity of the last UNREP, and last it should allow the operator to input a variable which will cause the scheduling algorithm to initiate an UNREP when the AOE is idle and a unit comes within some percentage above its flag level. These additions would better approximate actual battle group operations. The net result of these three changes would have been a slight increase in AST in some cases.

C. RECOMMENDATIONS

Understanding the mechanics behind UNREP and the two methods discussed in this paper will lead to integrating UNREP considerations into the tactics of warfighting. Battle group on station time can not and should not be assumed to be 100% no matter what formation or UNREP method if transit time is in excess of three days.

Employing tactics which would rotate the formation could provide additional AST. Keep the AOE under the protective umbrella of the CV and rotate the formation around the outer screen. As a unit of the outer screen requires refueling, bring it in to replace a unit of the inner screen. Send a topped off unit from the inner screen to the outer screen. The AOE would service only those units within the inner screen. However, this tactic would require units to have comparable capabilities. This new tactic offers promise and requires further study.

Another area of future research would be to further consider battle group screening effectiveness. When units depart their outer screen stations to UNREP screening effectiveness degrades gracefully, not abruptly. Similarly, as units get close to assigned stations after UNREP their screening effectiveness would increase to full value. At present this effect can be approximated in the model by specifying a patrol radius instead of a point station. However, in order to utilize the model feature, AAW and ASW experts must analyze and determine the best choice of radius to represent "on station" effectiveness.

While BFORM does not presently have complete flexibility, it is already very powerful and could be modified to model additional scenarios. The goal should be to blend screening effectiveness analysis with new UNREP tactics to achieve better, safer battle group operations. Readiness at the battle group level is more than some CASREP percentage, manning level, spare parts and stock on hand, or even training proficiency. Not only do we have to make do with what we have, but allocating what we have smartly will lead to the maximum battle group readiness. BFORM is a viable tactical aid which can and should be adopted now by the end user--the commands and their staff.

APPENDIX A

STEAMING FORMATIONS

Three steaming formations were formed using a low, reasonable, and high mix of combatants. This appendix contains those formations.

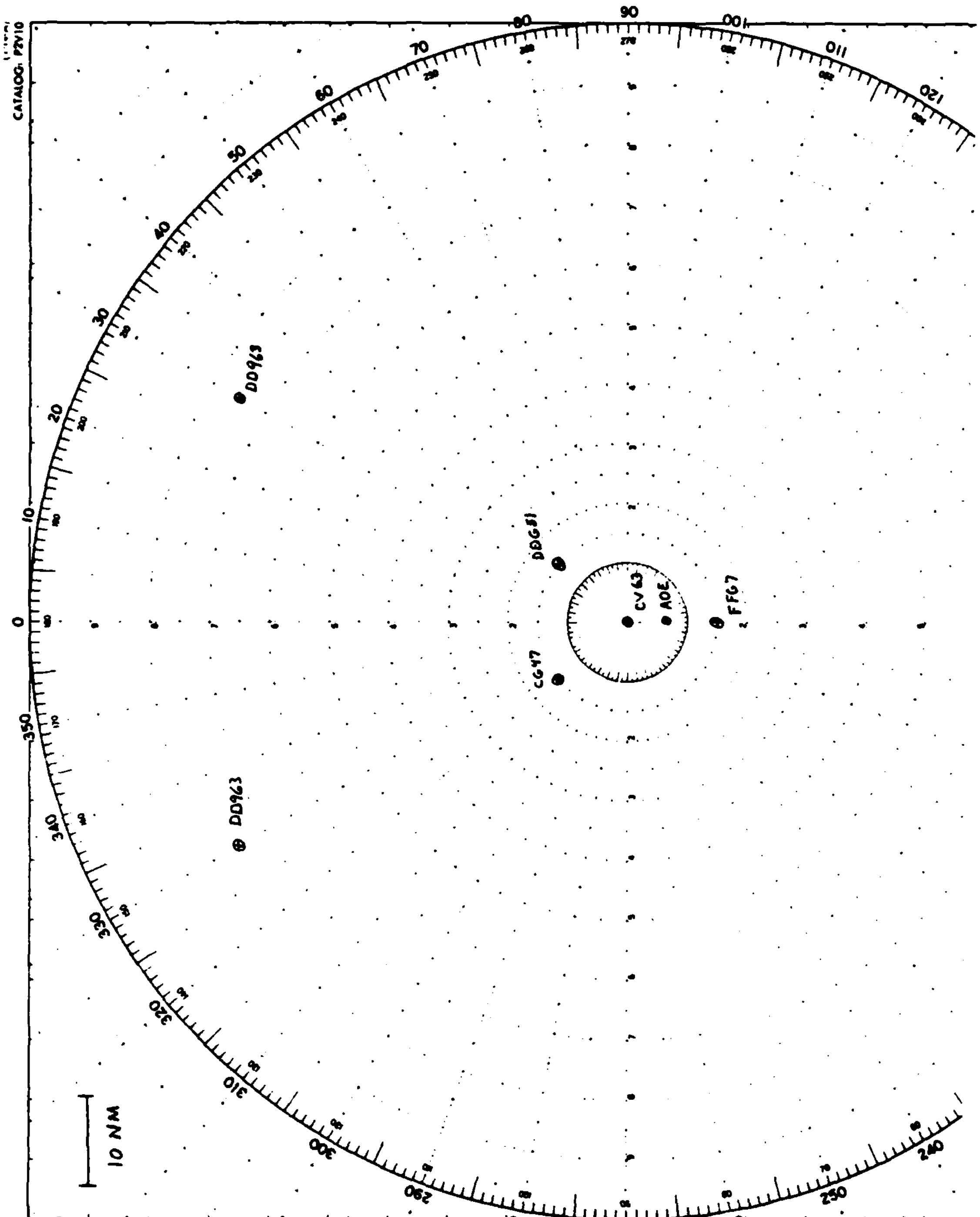

Figure 18. Formation A

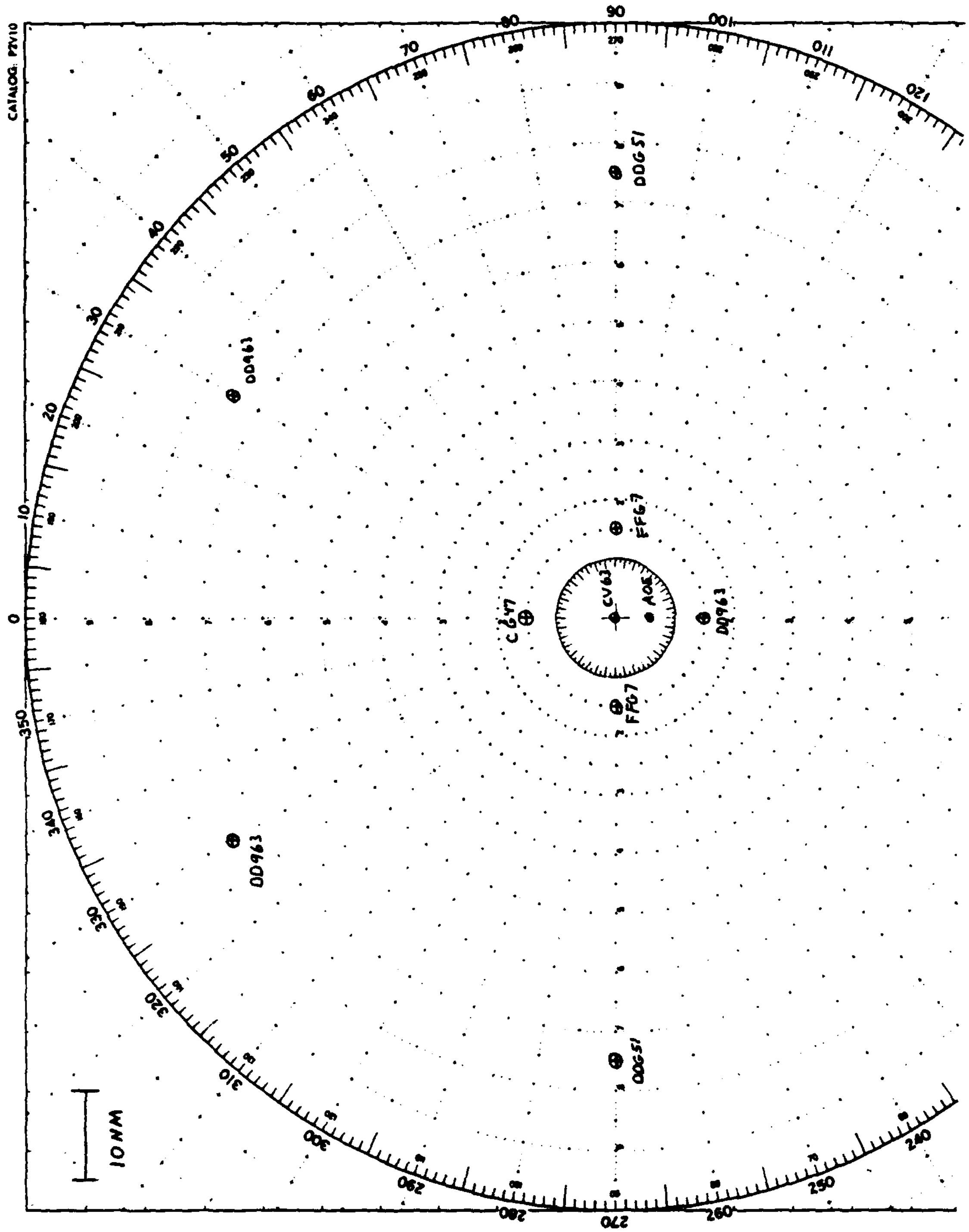

Figure 19. Formation B

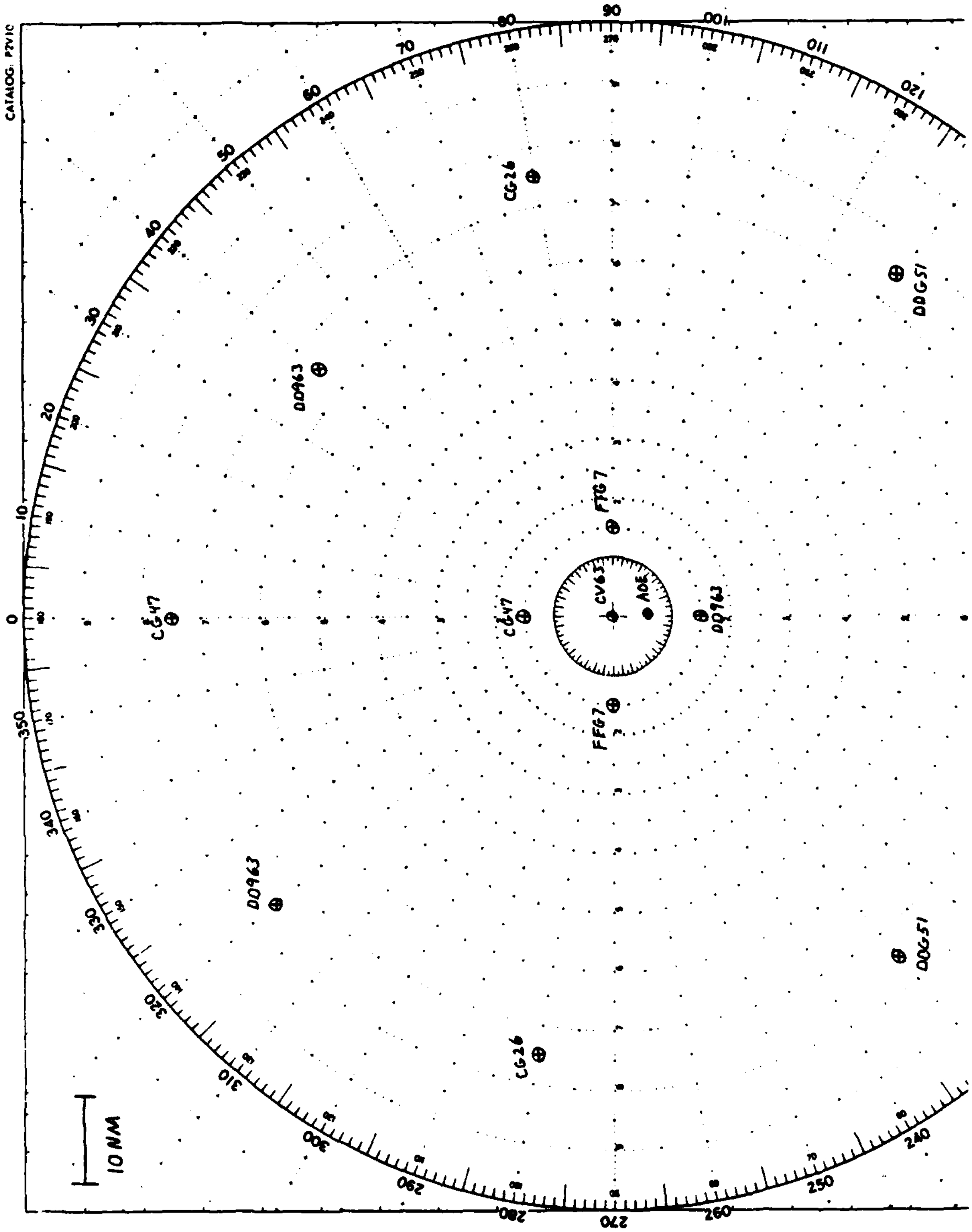

Figure 20. Formation C

APPENDIX B

TABLE 3. CHOSEN STARTING DFM LEVELS

COMBATANT	GROUP A	GROUP B	GROUP C
CV 63	90%	90%	90%
CG 47	95%	95%	85%/95%
DDG 51	70%	75%/85%	75%/90%
FFG 7	70%	70%/80%	70%/80%
DD 963	70%/85%	70%/75%/80%	70%/75%/80%
CG 26			70%/80%
AVERAGE	80%	80%	80%

APPENDIX C

COMPARISON BETWEEN THREE FLAG LEVELS

Figures 21, 22, and 23 plot, using a flag level set at 50, 65, and 80 percent respectively, AST vs duration of the simulation run. Figure 24 compares AST using formation B with flag levels set at 50 and 65 percent.

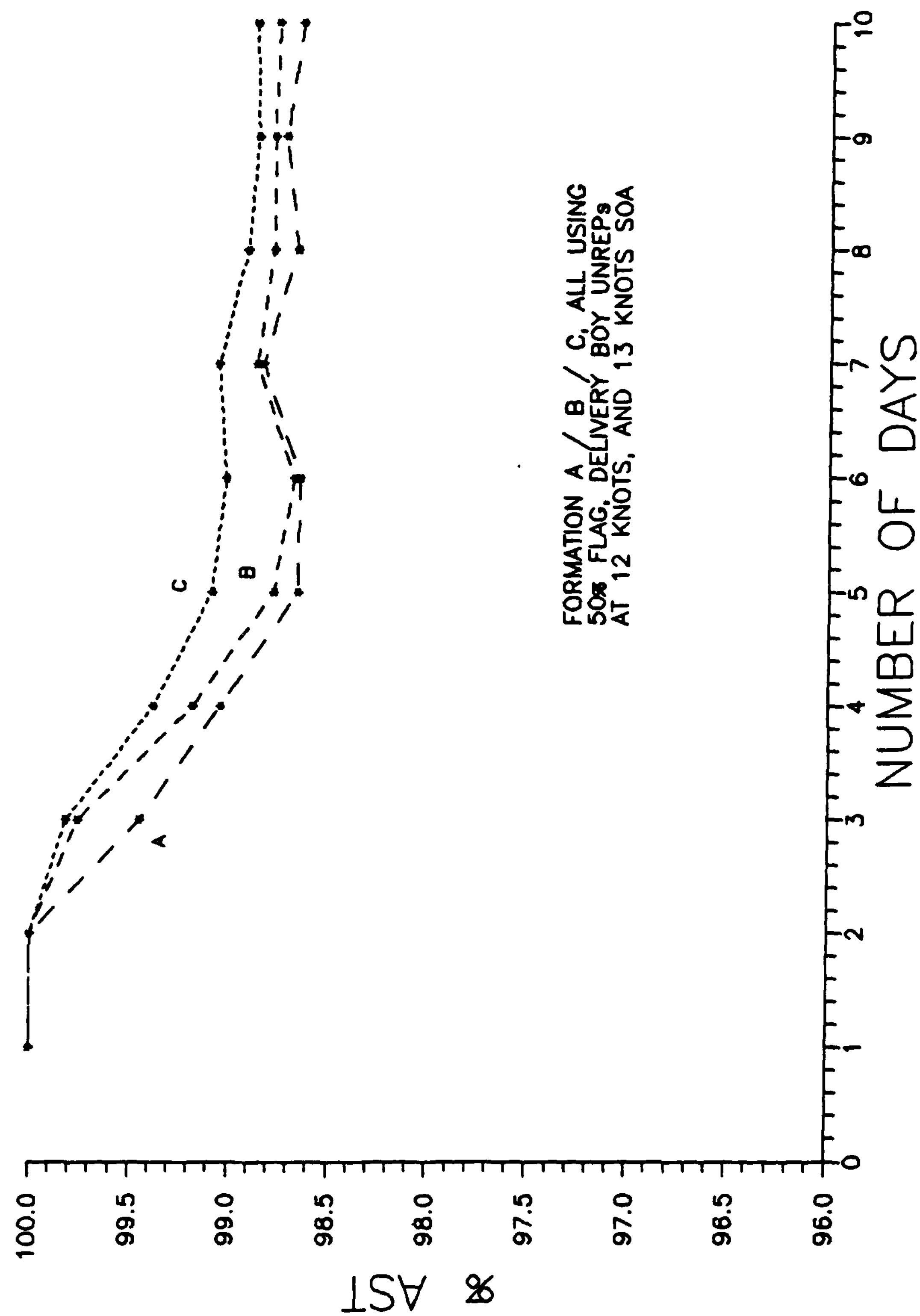

Figure 21. AST For 50% Flag

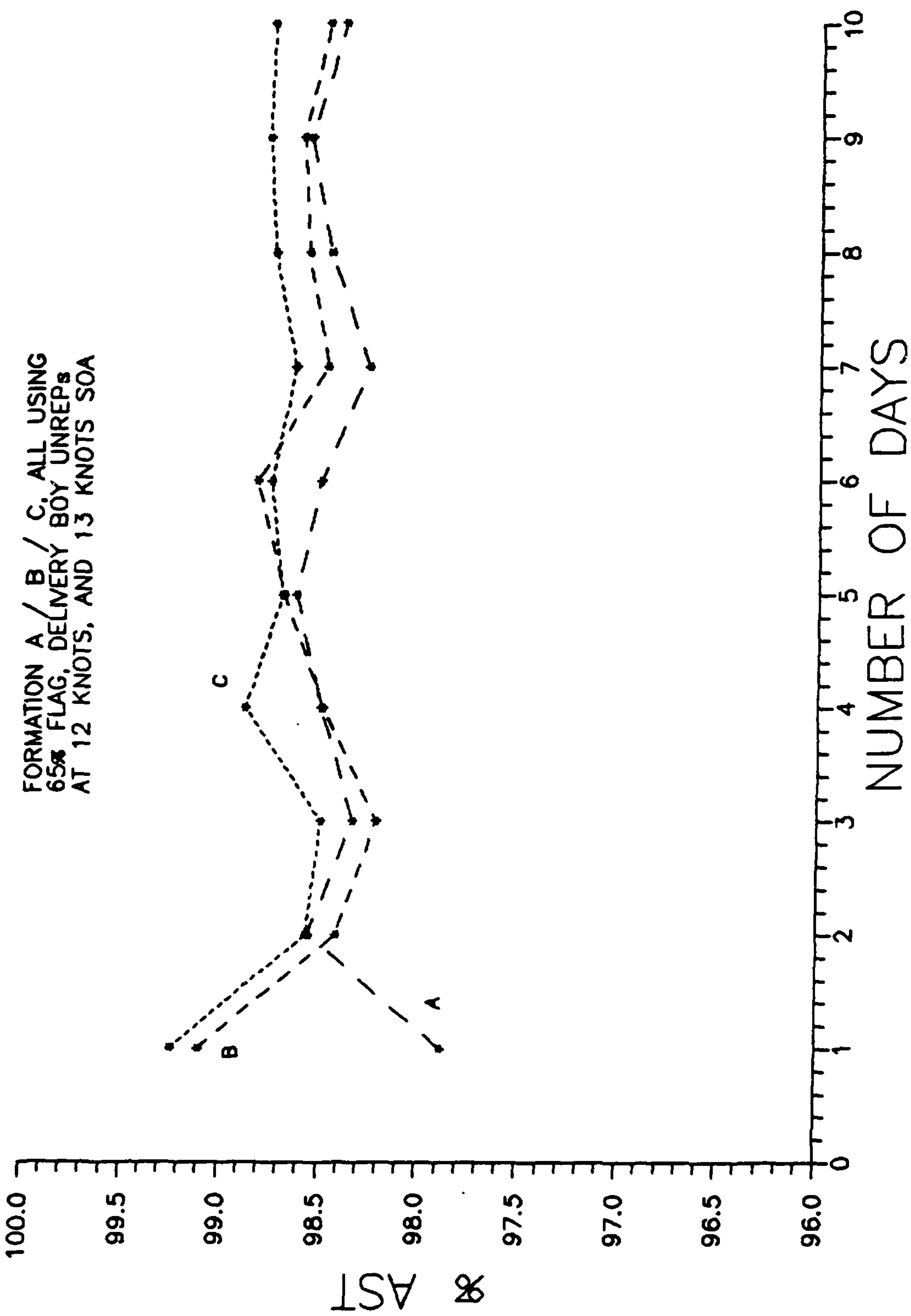

Figure 22. AST For 65% Flag

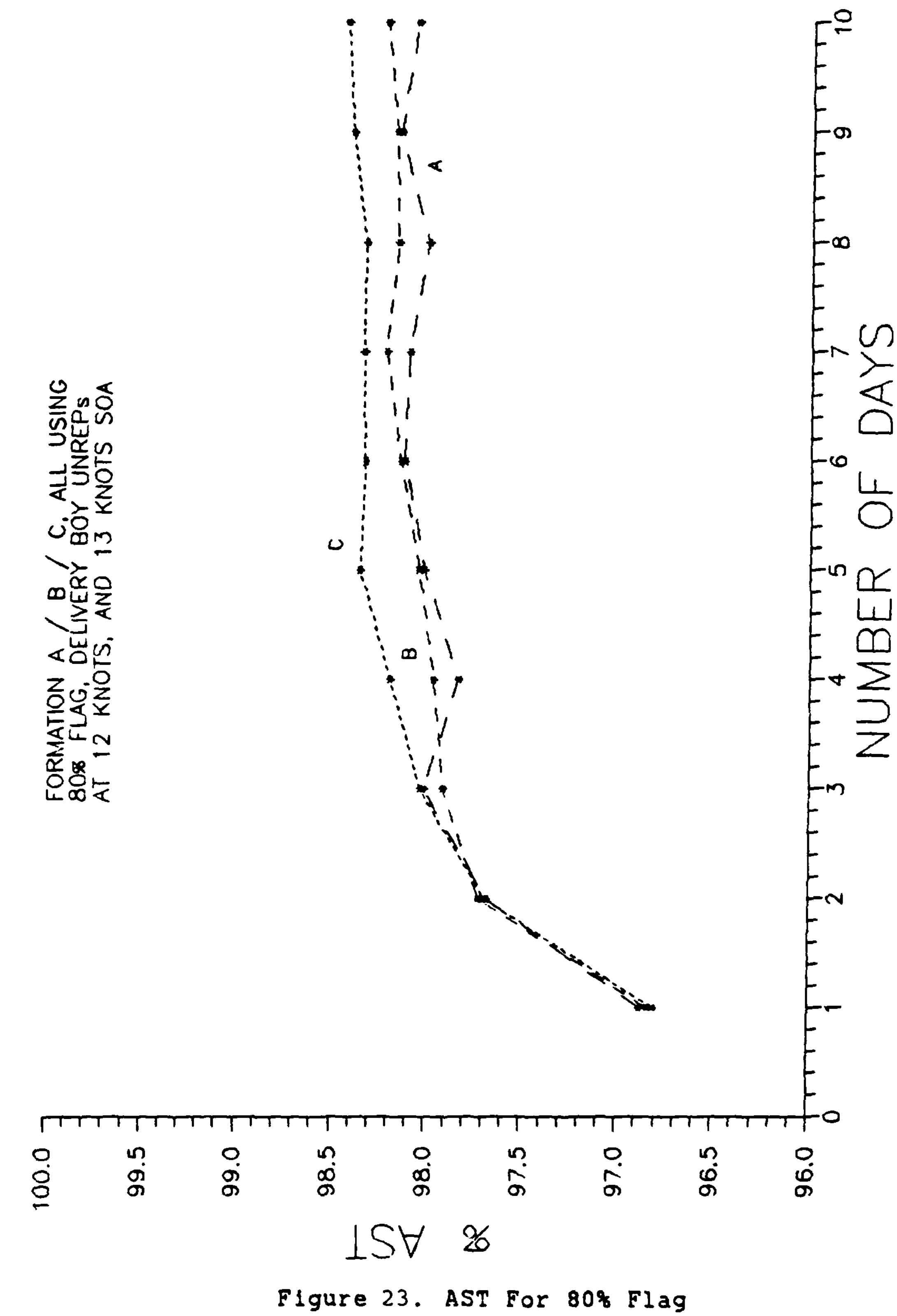

Figure 23. AST For 80% Flag

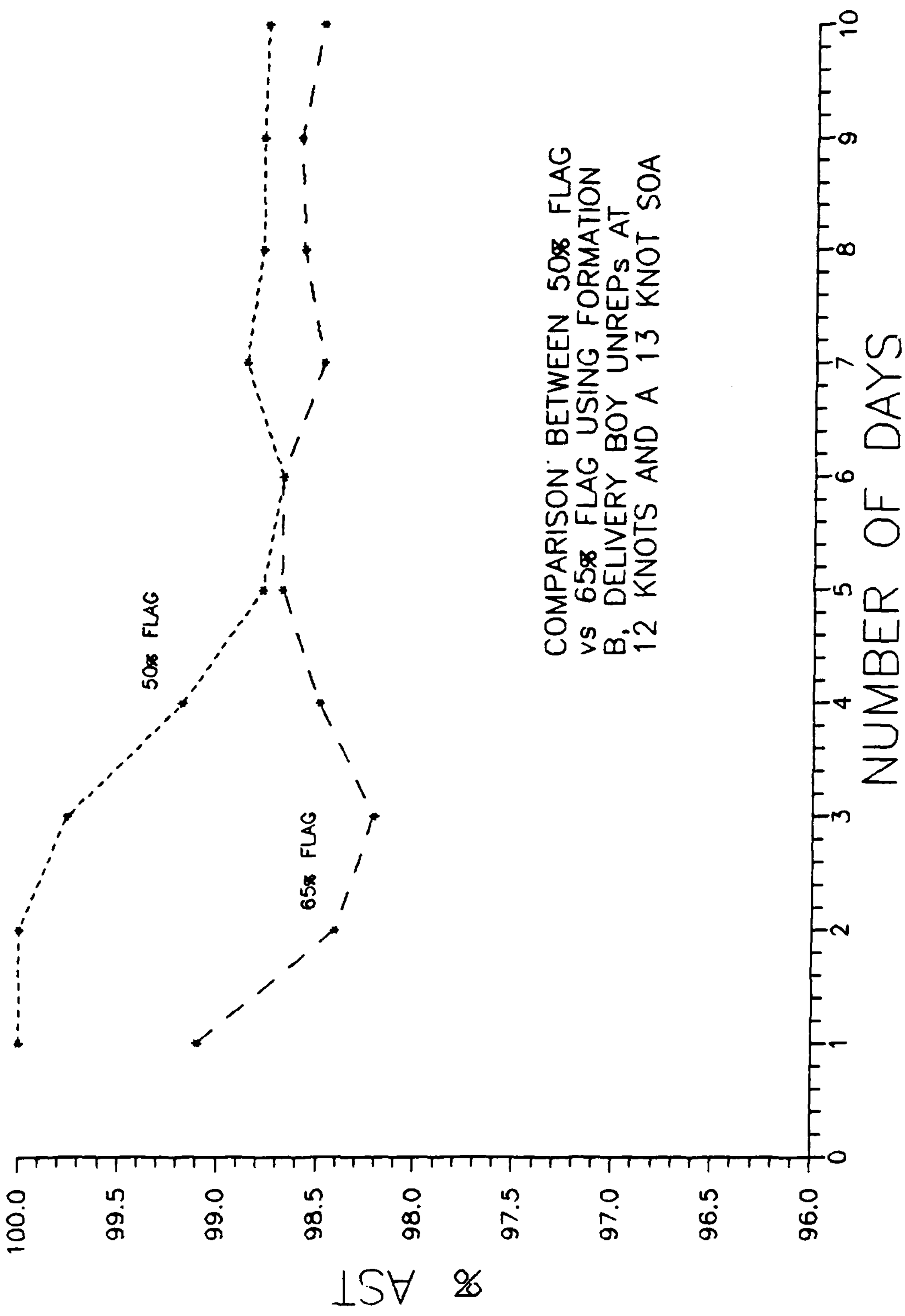

Figure 24. Comparison Between 50% and 65% Flag

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